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PROBLEMS AND SOLUTIONS

Annu Haapakangas

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Subjective Reactions to Noise in Open-Plan Offices and the Effects of Noise on Cognitive Performance Problems and Solutions

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ABSTRACT

This thesis examines the effects of noise on cognitive performance and subjective reactions in open-plan offices. Earlier research suggests that the acoustic distraction largely results from background speech that is irrelevant to the listener. Combining methods from psychology and room acoustic research, this thesis investigates speech intelligibility as a predictor of the negative effects of background speech and examines some design-related solutions to decreasing these problems. Speech intelligibility is described with the Speech Transmission Index (*STI*) and the distraction distance which is a room acoustic parameter based on the *STI*. Evidence from three laboratory experiments and two field studies is presented. The results show that the general perception of both disturbing noise (Study IV) and office distractions (Study V) is strongly correlated with disturbing background speech in open-plan offices. An increase in office distractions mediates negative changes in environmental satisfaction, perceived collaboration and stress symptoms following a move to a modern open-plan office (Study V). The laboratory studies (I, II and III) show that speech intelligibility predicts particularly subjective perceptions of acoustic disturbance but also performance in verbal short-term memory and working memory tasks. The observed performance results are compatible with the *STI*-performance model proposed by Hongisto (2005). More complex tasks with higher requirements on semantic processing were not affected (Studies I to III). In terms of the investigated solutions, the findings support the use of masking sound in increasing satisfaction with the acoustic environment (Studies I to IV). Filtered pink noise and spring water sound are effective and pleasant masking sounds whereas music cannot be recommended for general use (Study II). Together, Studies III and IV show that perceived noise disturbance can be decreased in open-plan offices by holistic room acoustic design. However, its benefits are limited at short distances between nearby workstations (Study III). Distraction distance predicts perceived noise disturbance in open-plan offices (Study IV), which supports its use in the evaluation and design of office acoustics. The provision of additional quiet workspaces is a complementary way of decreasing the negative effects of office distractions in modern open-plan offices (Study V). Limitations of this work and suggestions for future research are discussed.

Subjektiiviset reaktiot avotoimistojen meluun ja melun vaikutukset kognitiiviseen suoriutumiseen Ongelmia ja ratkaisuja

Annu Haapakangas

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TIIVISTELMÄ

Tämä väitöskirjatutkimus käsittelee melun vaikutuksia kognitiiviseen suoriutumiseen ja subjektiivisiin reaktioihin avotoimistoissa. Aiempien tutkimusten mukaan koetut akustiset ongelmat liittyvät suurelta osin sellaisiin puheääniin, jotka ovat kuulijan kannalta hyödyttömiä. Tässä tutkimuksessa selvitetään psykologisia ja huoneakustisia tutkimusmenetelmiä yhdistäen puheenerotettavuuden merkitystä puheen negatiivisten vaikutusten selittäjänä sekä tutkitaan toimistosuunnittelun keinoja ongelmien vähentämiseksi. Puheenerotettavuutta kuvataan puheensiirtoindeksillä ja häiritsevyyssäteellä, joka on puheensiirtoindeksiin perustuva huoneakustinen mittaluku. Tutkimus sisältää kolme kokeellista laboratoriotutkimusta ja kaksi kenttätutkimusta. Tulosten perusteella sekä häiritsevä melu (Tutkimus IV) että kokemus työympäristön häiriötekijöistä (Tutkimus V) korreloivat vahvasti puheäänten häiritsevyyden kanssa. Häiriötekijöiden lisääntyminen toimii välittävänä tekijänä suhteessa negatiivisiin muutoksiin ympäristötyytyväisyydessä, yhteistyön kokemisessa sekä stressioireissa avotoimistoon muuton jälkeen (Tutkimus V). Laboratoriotutkimukset (I, II ja III) osoittavat, että puheenerotettavuus ennustaa erityisesti akustisten olosuhteiden subjektiivista häiritsevyyttä, mutta myös suoriutumista verbaalisissa lyhytkestoisen muistin ja työmuistin tehtävissä. Kognitiivista suoriutumista koskevat tulokset ovat yhdenmukaisia Hongiston (2005) esittämän, puheensiirtoindeksin ja suoriutumisen suhdetta kuvaavan mallin kanssa. Kompleksisemmissa, enemmän semanttista prosessointia sisältävissä tehtävissä ei havaittu puheäänten vaikutuksia kognitiiviseen suoriutumiseen (Tutkimukset I-III). Tutkittujen ratkaisukeinojen osalta tulokset tukevat peiteäänen käyttöä akustisen tyytyväisyyden parantamisessa (Tutkimukset I-IV). Suodatettu kohina ja puronsolina ovat tehokkaita ja miellyttäviä peiteääniä, kun taas musiikkia ei voida suositella yleiseen käyttöön (Tutkimus II). Tutkimukset III ja IV osoittavat, että akustisia ongelmia voidaan vähentää kokonaisvaltaisella huoneakustisella suunnittelulla. Sen hyödyt ovat kuitenkin rajallisia lyhyillä etäisyyksillä lähityöpisteiden välillä (Tutkimus III). Häiritsevyyssäde selittää koettua melun häiritsevyyttä avotoimistoissa (Tutkimus IV), mikä tukee sen käyttöä toimistojen akustisten olosuhteiden arvioinnissa ja suunnittelussa. Työympäristön häiriötekijöiden negatiivisia vaikutuksia voidaan lisäksi vähentää rakentamalla avotoimistoihin vaihtoehtoisia hiljaisia työtiloja (Tutkimus V). Väitöskirjan lopussa tarkastellaan tutkimuksen rajoituksia sekä jatkotutkimustarpeita.

CONTENTS

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When I started working as a researcher in 2007, I did not know what room acoustics meant, and I certainly did not imagine doing my doctoral thesis about it. What motivated me was the possibility to do applied research that was directly linked to real workplaces and the realization that this was an area where psychological research was very much needed. After 10 years, it is satisfying to see that I have been able to develop expertise in this field that was not originally my 'comfort zone'. For that, I owe thanks to several people as I could never have done this on my own.

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Kaarina, 11th May 2017

Annu Haapakangas

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on five original articles. The articles are referred to in the text by the following Roman numerals:

I Haka, M., Haapakangas, A., Keränen, J., Hakala, J., Keskinen, E., & Hongisto, V. (2009). Performance effects and subjective disturbance of speech in acoustically different office types - a laboratory experiment. *Indoor Air, 19*(6), 454-467.

II Haapakangas, A., Kankkunen, E., Hongisto, V., Virjonen, P., Oliva, D., & Keskinen, E. (2011). Effects of five speech masking sounds on performance and acoustic satisfaction - implications for open-plan offices. *Acta Acustica united with Acustica*, *97*(4), 641-655.

III Haapakangas, A., Hongisto, V., Hyönä, J., Kokko, J., & Keränen, J. (2014). Effects of irrelevant speech on performance and subjective distraction: The role of acoustic design in open-plan offices. *Applied Acoustics*, *86*, 1-16.

IV Haapakangas, A., Hongisto, V., Eerola, M., & Kuusisto, T. (2017). Distraction distance and perceived disturbance by noise - An analysis of 21 open-plan offices. *Journal of the Acoustical Society of America, 141*(1), 127-136.

V Haapakangas, A., Hongisto, V., Varjo, J., & Lahtinen, M. (2016). Benefits of alternative workspaces in open-plan offices with fixed workstations – evidence from two office relocations. (Manuscript submitted for publication)

ABBREVIATIONS

$D_{2,S}$	Spatial decay rate of speech
dBA	A-weighted decibel
FTE	Full-time equivalent employee
ICT	Information and communications technology
ISE	Irrelevant sound effect
$L_{p,A,B}$	Average A-weighted SPL of background noise
$L_{p,A,S,4m}$	A-weighted SPL of speech at a 4-meter distance from the speaker
r_D	Distraction distance
SPL	Sound pressure level
STI	Speech Transmission Index
WM	Working memory

1. INTRODUCTION

Acoustic conditions are an inherent challenge of open-plan offices. While the absence of walls eases contact between employees, it also exposes them to noise and other distractions which may have various negative effects on them. Dissatisfaction with the acoustic conditions has been documented since the beginning of open-plan offices (e.g., Becker, Gield, Gaylin, & Sayer, 1983; Brookes & Kaplan, 1972; Hundert & Greenfield, 1969; Kaarlela-Tuomaala, Helenius, Keskinen, & Hongisto, 2009; Nemecek & Grandjean, 1973; Pierrette, Parizet, Chevret, & Chatillon, 2015; Sundstrom, Town, Rice, Osborn, & Brill, 1994). Is noise still an issue in contemporary offices? Does it affect the performance of employees and their subjective reactions to the work environment? And, most importantly, how can the acoustic problems be decreased?

Researchers are challenged by the interdisciplinary nature of these problems: understanding the effects of office acoustics on employees requires expertise on both people and buildings. But, as noted by Veitch, Charles, Farley, and Newsham (2007), researchers who are trained in the measurement of the physical environment often lack the skill of measuring behavioural responses, while psychologists are ill-equipped to quantify the physical environment. As a result, there has been relatively little research that is both of high scientific quality and relevant for the practical evaluation and design of open-plan offices.

This thesis takes an interdisciplinary and practically oriented approach. Cognitive psychology, environmental psychology and room acoustic research are combined to examine both problems and possible solutions related to office noise. Evidence from laboratory experiments and field studies are combined to gain a balanced and more reliable view of these issues. The focus is on the effects of the acoustic conditions, particularly irrelevant background speech, on cognitive performance and subjective reactions, such as perceived disturbance and stress. The thesis focuses on individual performance requiring concentration, not on collaborative tasks.

1.1 The background of contemporary open-plan office design

Open-plan offices were widely introduced in the 60s although Taylorism affected the adoption of similar work spaces in North America already in the early twentieth century (Duffy, 1997). In Finland, the popularity of open-plan offices has increased since the 90s (RIL 243-3, 2008). The term 'open-plan office' should be understood as a very general category within which offices may differ in several factors, such as functional and architectural features, office size, workstation density and office use (i.e., assigned versus shared workstations). The distinction between shared rooms and small open-plan offices is not clear, as rooms of 4 to 6 workers have been defined in both categories (Bodin Danielsson & Bodin, 2009; Pejtersen, Allermann, Kristensen, & Poulsen, 2006).

Throughout its history, the development of open-plan offices has been affected by economic issues, technological development, management theories and architectural trends (Danielsson, 2005; Davis, Leach, & Clegg, 2011; Duffy, 1997). At the moment, the popularity of open-plan offices is supported by several trends. Space-efficiency is pursued to decrease maintenance and rental costs as well as energy use. As a result of the rapid technological development, workers are less bound to a specific workspace and need less space for storage and working, which reduces the need for private rooms, or even a personal workstation. Shared office space is also perceived as compatible with the emphasis of collaboration in increasing knowledge work (Davis et al., 2011).

The design of open-plan offices has also evolved. Contemporary open-plan designs tend to include alternative workspaces for different tasks, such as spaces for collaboration, quiet working, private discussions, and phone calls (Davis et al., 2011). In many offices, workers no longer have personal workstations but switch between settings depending on their activities. These non-territorial offices, referred to as activity-based (Appel-Meulenbroek, Groenen, & Janssen, 2011) or flexible offices (Bodin Danielsson & Bodin, 2008, 2009; van der Voordt, 2004), are accompanied by so-called 'new ways of working', which include increased freedom in the time and location of work, the use of advanced information and communications technology (ICT), and related changes in the organizational culture and management (Blok, Groenesteijn, Schelvis, & Vink, 2012). Due to the differences in office spaces and the working style, activity-based offices are considered as a different category from traditional open-plan offices (e.g., Bodin Danielsson & Bodin, 2008, 2009) even though both office types contain similar open workspaces. Some features of activity-based offices, such as additional quiet workspaces, can also be adopted in open-plan offices. Thus, many contemporary offices are hybrids between these prototypic categories (Bodin Danielsson, Bodin, Wulff, & Theorell, 2015), making the definition of modern office designs difficult[1].

1 The definition of modern office types is also complicated by some variation in the use and interpretation of terms. *Flexible offices* are non-territorial, whereas the term *activity-based office* is occasionally used in a more general sense to incorporate similar offices with personal workstations (e.g., Bodin Danielsson et al., 2015). In Finland, activity-based offices and open-plan offices with additional workspaces are referred to as *multi-space offices*. This term has been used in the international literature (e.g., Boutellier, Ullman, Schreiber, & Naef, 2008) but it is poorly defined and not widely recognised. Activity-based offices with personal workstations have been referred to as *combi-offices* by Dutch researchers (e.g., De Been & Beijer, 2014; Vos & van der Voordt, 2001), while the definition for *combi-office* used by Swedish researchers may include workers in private office rooms (e.g., Bodin Danielsson & Bodin, 2008, 2009). The terms *combi-office* and *multi-space office* are generally avoided in this thesis because of their ambiguity.

Together, the trends in office design mean that the use of open-plan workspaces is expanding to all sectors of working life, including universities, courts, hospitals and other expert organizations which involve highly demanding knowledge work. For example, the Finnish Government Premises Strategy 2020 aims at the space use of 15-18 m^2 per a full-time equivalent employee which, in practice, requires wide adoption of open-plan or activity-based offices in the public sector. At the same time, the acoustic design of open-plan offices lacks behind. In Finland, the National Building Code (C1:1998) does not include obligatory requirements specifically for open-plan offices. The room acoustic requirements of the Building Code are based on private office rooms where noise originates mainly from ventilation or outside the office space. As the following literature review will show, the acoustic challenges of open-plan offices are essentially different.

1.2 The problems of open-plan offices observed in field studies

The existing literature associates open-plan offices with a variety of negative outcomes that range from specific environmental complaints to problems concerning worker performance and well-being. These findings include noise (Nemecek & Grandjean, 1973; Pejtersen et al., 2006), lack of privacy (De Croon, Sluiter, Kuijer, & Frings-Dresen, 2005; Sundstrom, Herbert, & Brown, 1982), other indoor environmental complaints (Kim & de Dear, 2013; Pejtersen et al., 2006), decreased satisfaction with the environment (Haapakangas, Helenius, Keskinen, & Hongisto, 2008; Kaarlela-Tuomaala et al., 2009), increased stress symptoms and other health-related complaints (Bergstrom, Miller, & Horneij, 2015; Bodin Danielsson & Bodin, 2008; Hedge, 1984; Herbig, Schneider, & Nowak, 2016; Pejtersen et al., 2006), increased cognitive workload (De Croon et al., 2005), decrease in self-estimated work performance (Bergstrom et al., 2015; Kaarlela-Tuomaala et al., 2009), lower job satisfaction (Bodin Danielsson & Bodin, 2008; De Croon et al., 2005), problems in interpersonal relations (Bodin Danielsson et al., 2015; De Croon et al., 2005) and increased sickness absence (Bodin Danielsson, Chungkham, Wulff, & Westerlund, 2014; Pejtersen, Feveile, Christensen, & Burr, 2011). Most of this evidence is based on cross-sectional studies comparing open-plan offices with private offices and other office types (e.g., Bodin Danielsson & Bodin, 2008; Kim & de Dear, 2013; Pejtersen et al., 2006) and on before-after comparisons involving a relocation from private offices to an open-plan environment (e.g., Bergstrom et al., 2015; Kaarlela-Tuomaala et al., 2009). Moving from private office rooms to an open-plan office generally increases employee dissatisfaction (e.g., Bergstrom et al., 2015; Kaarlela-Tuomaala et al., 2009; Oldham & Brass, 1979; Sundstrom et al., 1982; Zalesny & Farace, 1987), with few exceptions (e.g., Spreckelmeyer, 1993).

The key sources for dissatisfaction in open-plan offices are noise and lack of privacy (e.g., Bodin Danielsson & Bodin, 2009; Brookes & Kaplan, 1972; De Croon et al., 2005; Haapakangas et al., 2008; Pejtersen et al., 2006; Sundstrom et al., 1982). Noise refers to sound that is unwanted because it is unpleasant, interferes with important activity or is believed to be harmful (Kryter, 1970, in Cohen & Weinstein, 1981). Annoyance with noise is enhanced by the unpredictability, uncontrollability and uselessness of the sound (Kjellberg, Landström, Tesarz, Söderberg, & Akerlund, 1996). Thus, the perception of sound as noise is a psychological phenomenon. Of the different sounds in open-plan offices, co-workers' conversations and phones ringing are typically rated as the most disturbing (Banbury & Berry, 2005; Jensen & Arens, 2005; Kaarlela-Tuomaala et al., 2009; Pierrette et al., 2015; Schlittmeier & Liebl, 2015; Sundstrom et al., 1994). However, noise levels are not objectively particularly high in open-plan offices compared with many other occupational settings. The average noise levels in contemporary offices range from 46 to 58 dBA (Navai & Veitch, 2003), whereas noise exposure of 58-69 dBA has been reported in schools during lessons (Lundquist, Holmberg, & Landstrom, 2000) and 70 dBA is exceeded in daycare centers (Södersten, Granqvist, Hammarberg, & Szabo, 2002).

In office studies, noise has typically not been studied separately but as part of a variable for privacy (e.g., Newsham, Veitch, & Charles, 2008; Veitch et al., 2007; Zalesny & Farace, 1987). Perceived privacy refers to the sense of control over access to oneself (or one's group) or to information about oneself (Altman, 1975; Laurence, Fried, & Slowik, 2013). It is a psychological state that reflects the successfulness of a regulatory process by which an individual tries to balance the level of social contact with his or her needs (Laurence et al., 2013; Sundstrom, Burt, & Kamp, 1980). Perceived privacy is affected by architectural elements providing visual and auditory isolation, such as walls, distance, and screens around the workstation (Laurence et al., 2013; O'Neill & Carayon, 1993; Sundstrom et al., 1980). Thus, annoyance with noise is correlated with perceived lack of privacy (Pierrette et al., 2015; Sundstrom et al., 1980; Veitch et al., 2007). Speech privacy is one aspect of architectural privacy and refers to the extent that the acoustic conditions enable conversations that are not overheard. This concept is often used in room acoustic studies and design. High speech privacy equals conditions where noise intrusion from the environment is low.

As the problems of open-plan offices range from specific environmental complaints to various detriments of work performance and well-being, it is likely that there are causal processes by which the initial environmental complaints may, in some circumstances, develop into other problems. Noise and lack of privacy are possible causes for other negative outcomes because they are consistently observed in open-plan offices and co-occur with other complaints. However, there has been little research that has specifically tried to distinguish the role of noise in other problems. Sundstrom et al. (1994) surveyed 58 office sites before and after an office renovation and observed that environmental and job satisfaction decreased among employees who experienced an increase in noise, but not among others. A structural equation model (SEM) by Veitch et al. (2007) suggests that satisfaction with privacy and acoustics is linked to job satisfaction through satisfaction with the environment. Another SEM study (Lee, Lee, Jeon, Zhang, & Kang, 2016) associated noise disturbance with self-rated health. Herbig et al. (2016) and Laurence et al. (2013) observed that the association between architectural privacy (e.g., office type) and self-assessed physical and mental health is mediated by perceived privacy. Bodin Danielsson et al. (2015) found that noise disturbance is associated with an increased risk of conflicts in certain open-plan office types although noise did not completely explain the relation between office type and conflicts. However, these studies are mainly based on correlational study designs and only a few focus specifically on noise instead of acoustic or overall privacy.

A few field experiments have approached the issue by examining whether acoustic improvements are followed by positive changes in acoustic perceptions and other outcomes (Helenius & Hongisto, 2004; Hongisto, 2008; Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016; Keighley & Parkin, 1979; Seddigh, Berntson, Jönsson, Danielson, & Westerlund, 2015). While the results have been modest in some studies (e.g., Helenius & Hongisto, 2004), a few studies have observed improvements in acoustic perceptions but also in other outcomes, such as environmental satisfaction (Hongisto, Haapakangas, et al., 2016) and cognitive stress (Seddigh, Berntson, et al., 2015). However, these case studies involve several methodological limitations, such as small samples and poor control over confounding factors.

1.3 Experimental research on the effects of office noise

The effects of office noise have also been studied in laboratory conditions. The benefit of this approach is the experimental control which enables causal inference and an objective assessment of the performance effects of office noise. The limitations concern the generalisability of laboratory findings to workplaces and the restriction to the immediate effects of noise. A few of these studies have tested office noise exposure as such, either comparing office noise with a quiet control condition (e.g., Evans & Johnson, 2000; Kristiansen et al., 2009; Toftum, Lund, Kristiansen, & Clausen, 2012; Witterseh, Wyon, & Clausen, 2004) or varying the level of office noise (Jahncke, Hygge, Halin, Green, & Dimberg, 2011). These studies have provided some evidence for the cognitive, psychophysiological and subjective effects of office noise although the results are inconclusive.

1.3.1 Cognitive effects of background speech

Another approach has focused on the effects of background speech (e.g., Ebissou, Parizet, & Chevret, 2015; Jahncke, Hongisto, & Virjonen, 2013; Schlittmeier & Liebl, 2015; Smith-Jackson & Klein, 2009). This approach is also adopted in this thesis. The operationalization of office noise as background speech is supported by two lines of evidence: field studies highlighting speech as the main source of annoyance (e.g., Banbury & Berry, 2005; Kaarlela-Tuomaala et al., 2009; Sundstrom et al., 1994) and basic research demonstrating the detrimental impacts of speech on cognitive performance (for a meta-analysis, see Szalma & Hancock, 2011). Much of the latter evidence comes from studies on the *irrelevant sound effect* (*ISE*, e.g., Colle & Welsh, 1976; Jones, Madden, & Miles, 1992; Salamé & Baddeley, 1982). The term refers to the disruption of a particular short-term memory task, *serial recall*, in the presence of speech or other variable sound which the individual is instructed to ignore. In this task, a series of items (e.g., digits, letters) is presented one at a time after which the participant has to recall them in exactly the same order. In the following, the term 'irrelevant speech' will only be used when referring to the *ISE* while the term 'background speech' will be used generally for unattended, unnecessary speech.

Background speech also impairs several other tasks including reading comprehension (Martin, Wogalter, & Forlano, 1988; Sörqvist, Halin, & Hygge, 2010), memory for prose (Banbury & Berry, 1998; Halin, Marsh, Hellman, Hellström, & Sörqvist, 2014), proofreading (Jones, Miles, & Page, 1990; Venetjoki, Kaarlela-Tuomaala, Keskinen, & Hongisto, 2006), writing (Sörqvist, Nöstl, & Halin, 2012) and mental arithmetic (Banbury & Berry, 1998; Schlittmeier, Hellbrück, Thaden, & Vorländer, 2008). A meta-analysis by Szalma and Hancock (2011) concluded that, overall, the cognitive impact of speech is more damaging than that of non-speech noise and intermittent speech is more detrimental than continuous speech.

1.3.2 Theories explaining the performance effects of background speech

Why does background speech impair performance? According to Hughes and Jones (2003), auditory distraction is related to a tension between two important functions: 1) the ability to maintain attention in a deliberate, goal-oriented way while ignoring other stimuli (e.g., concentrating on a work task) and 2) the ability to flexibly shift attention when new relevant information emerges and requires a response (e.g., your boss calls your name). This flexibility requires that the information that is not deliberately attended is yet processed and organised to some extent by the perceptual system. The susceptibility to distraction is a cost of this pre-attentive processing. The auditory modality is particularly susceptible to distraction because it receives information from all directions and processes it automatically as opposed to visual stimuli which can be avoided by shifting gaze or closing the eyes.

The theories on the exact mechanisms of auditory distraction are typically categorised into *interference-by-content* and *interference-by-process accounts* (e.g., Marsh, Hughes, & Jones, 2008, 2009; Perham, Hodgetts, & Banbury, 2013). The *interference-by-content* accounts assume that distraction results from the similarity of identity (i.e., content) between the items in the task and in the background speech. For example, within the working memory model of Baddeley (e.g., Baddeley, 1983; Salamé & Baddeley, 1982) it was assumed that background speech had direct access to the phonological store where the phonological codes for the task items were represented, corrupting memory traces for the task items. However, the interference-by-content view has been challenged by several empirical findings that cannot be explained within this framework (see Jones & Tremblay, 2000; Marsh et al., 2009; Marsh & Jones, 2010).

In contrast, the *interference-by-process account* proposes that the performance effects depend on the extent to which the task and sound compete for the same cognitive processes (e.g., Jones & Tremblay, 2000). In the classic *ISE*, the disruption is assumed to result from two conflicting processes of seriation (i.e., the maintenance of order). Specifically, it is assumed that the automatic, pre-attentive perception of changing elements in an auditory stream yields clues to order, conflicting with the deliberate processing of serial information in the memory task (Banbury, Macken, Tremblay, & Jones, 2001; Jones, Macken, & Murray, 1993). This effect is produced by any varying sound and depends on the degree of variability, hence referred to as *the changing-state effect* (e.g., Jones et al., 1992; Jones & Macken, 1993). The effect of irrelevant speech on serial recall merely results from the acoustic variability, not the semantic features. Process-based interference also extends to other types of tasks. The semantic characteristics of background speech explain the interference in tasks that require semantic processing, such as proofreading (Jones et al., 1990), reading comprehension (Oswald, Tremblay, & Jones, 2000), writing (Sörqvist et al., 2012) and semantic memory (Marsh et al., 2008, 2009).

Attentional capture is yet another explanation for the effects of background sounds (Cowan, 1995). Based on psychophysiological research tradition (e.g., Sokolov, 1963), the performance effects are assumed to result from an orienting response to an auditory event that deviates from the recent auditory past. Performance disruption is assumed to occur because attention is diverted to the new stimulus.

According to *the duplex-mechanism account* (Hughes, 2014; Hughes, Vachon, & Jones, 2007), attentional capture and interference-by-process are not competing explanations but represent functionally different mechanisms. Attentional capture is a general mechanism that can occur in any task – as long as the task requires attention. In contrast, the interference-by-process phenomenon is a joint product of the task demands and the properties of the sound. One essential difference between these phenomena concerns the possibility of top-down control: attentional capture can be inhibited, for example, by increased task engagement, whereas process-based interference cannot (Hughes, 2014).

It should be noted that the present thesis does not test these theories. The theories are reviewed because they present several plausible mechanisms for the effects of background speech, thus supporting the research questions of this thesis. The theories have implications for the selection of appropriate tasks and the interpretation of results.

1.4 Speech intelligibility as a predictor of the effects of background speech

When speech is the noise source, its cognitive impact does not depend on the noise level, but on *speech intelligibility* (Colle, 1980; Ellermeier & Hellbrück, 1998; Schlittmeier et al., 2008). Speech intelligibility refers to the proportion of speech material (e.g., syllables, words) that is correctly perceived. It can be determined by subjective listening tests or described with a physical parameter, such as the signal-to-noise ratio. The disruptive effect of background speech on cognitive performance increases with increasing speech intelligibility (Colle, 1980; Ellermeier & Hellbrück, 1998; Schlittmeier et al., 2008). Even at the sound levels of a whisper, performance effects depend on how intelligible speech is (Hongisto, Varjo, Leppämäki, Oliva, & Hyönä, 2016; Schlittmeier et al., 2008).

The concept of speech intelligibility is central to this thesis for several reason. First, employees in open-plan offices are exposed to varying levels of intelligible speech because of varying distance to speech sources. Speech intelligibility also varies between open-plan offices due to their room acoustic differences (Virjonen, Keränen, & Hongisto, 2009). Thus, speech intelligibility is relevant for describing noise exposure in open-plan offices. Second, it is important to determine the level of speech intelligibility at which the detrimental effects of background speech occur. Such information is needed for setting objective criteria for the acoustic quality of offices. The vast literature from basic research does not provide information on critical speech intelligibility levels because it focuses on examining highly intelligible speech in relation to silence. Third, the central role of speech intelligibility has implications for the way that acoustic problems are solved. The typical response to noise complaints is to try to reduce the noise level, for example, by adding absorption materials. Such solutions alone are ineffective in reducing the distraction caused by speech because they do not always decrease speech intelligibility, but can, in the worst case, result in the opposite (Virjonen, Keränen, Helenius, Hakala, & Hongisto, 2007).

Speech intelligibility can, however, be decreased by a more holistic acoustic design that considers several room characteristics simultaneously (Bradley, 2003; Keränen, Hongisto, Oliva, & Hakala, 2012; Keränen & Hongisto, 2013; Virjonen et al., 2009).

1.4.1 Previous studies on the role of speech intelligibility

When Study I of this thesis (Haka et al., 2009) was published, only four experiments had examined the cognitive effects of background speech varying in intelligibility (Colle, 1980; Ellermeier & Hellbrück, 1998; Schlittmeier et al., 2008; Venetjoki et al., 2006). The earliest studies showed that performance in serial recall was affected by speech intelligibility (Colle, 1980; Ellermeier & Hellbrück, 1998; Schlittmeier et al., 2008). Similar effects were later reported in a mental arithmetic task (Schlittmeier et al., 2008) and proofreading (Venetjoki et al., 2006). Several studies have since supported the assumption of the association between speech intelligibility and performance (Brocolini, Parizet, & Chevret, 2016; Ebissou et al., 2015; Hongisto, Varjo, et al., 2016; Jahncke et al., 2013; Keus van de Poll, Ljung, Odelius, & Sörqvist, 2014; Keus van de Poll et al., 2015; Liebl, Assfalg, & Schlittmeier, 2016; Schlittmeier & Hellbrück, 2009). In the following, I will focus on reviewing speech intelligibility studies that had been published when research for this thesis was conducted. More recent studies will be discussed in relation to the results of this thesis in the Discussion section.

1.4.2 The application of Speech Transmission Index in experimental studies

The research in this area was facilitated by Hongisto (2005) who published a hypothetical model on the relation between speech intelligibility and cognitive performance. The model uses the Speech Transmission Index (*STI,* IEC 60268-16, 2003) as a descriptor of speech intelligibility. The *STI* is an objective parameter that is determined from the sound pressure levels (*SPL*) of speech and background noise and the early decay time of the room (Hongisto, Keränen, & Larm, 2004). Its value varies between 0.0 (no intelligibility) and 1.0 (perfect intelligibility). The *STI* is associated with the subjective intelligibility of speech, determined with listening tests (IEC 60268-16). Speech intelligibility can also be quantified in other ways, such as the signal-to-noise ratio, and other speech intelligibility parameters, such as the Articulation Index (ANSI S3.5, 1969) and the Speech Intelligibility Index (ANSI S3.5, 1997). The benefit of such parameters is that they can also be applied in room acoustic design. Thus, the *STI* provides a way of linking experimental laboratory manipulations to the acoustic evaluation and development of open-plan offices.

Hongisto's (2005) model proposes a hypothetical curve for the relation between cognitive performance and the *STI*, shown in **Figure 1**. Hongisto assumed that performance begins to decrease when the *STI* exceeds 0.20 and reaches the maximum level of impairment at *STI* 0.60. The decrease in performance is assumed to be steepest between *STI* 0.30 and 0.50. Hongisto (2005) concluded that the *STI* should be below 0.50 in order for the detrimental impact of speech to decrease. This assumption was adopted in the international measurement standard for open-plan office acoustics (ISO 3382-3), published in 2012. Despite its influence, the model was based on only a few studies due to the lack of research at the time. Thus, more research has been needed to evaluate the assumptions of Hongisto's (2005) model.

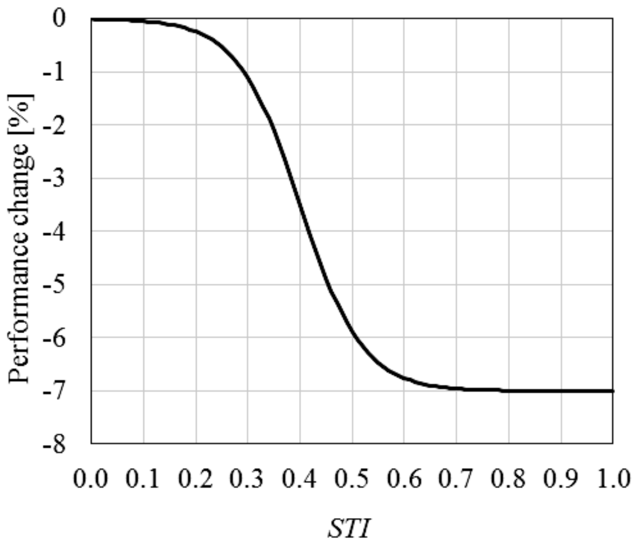

Figure 1. The prediction model by Hongisto (2005), showing the assumed decrease in performance as a function of the *STI*. The decrease in performance is determined by subtracting the error percentage in speech (*STI*>0.00) from the error percentage in silence (*STI* 0.00).

When the research for this thesis began, only Venetjoki et al. (2006) had used the *STI* as a descriptor of speech intelligibility in cognitive experiments of office noise. Venetjoki et al. (2006) showed that proofreading performance deteriorated between *STI* 0.30 and 0.80. This result fits the general shape of Hongisto's (2005) model although Venetjoki et al. (2006) did not test the critical values of the model (i.e., values around 0.50). Background speech did not affect elementary cognitive processes, such as attention and processing speed, nor reading comprehension although the latter could have resulted from the low difficulty of the task.

1.4.3 Speech intelligibility and subjective disturbance

Speech intelligibility also predicts subjective responses to acoustic conditions, such as the perceived disturbance of the sound environment (Schlittmeier et al., 2008), acoustic satisfaction (Veitch, Bradley, Legault, Norcross, & Svec, 2002) and cognitive workload (Ebissou et al., 2015). Subjective measures are typically more sensitive in detecting differences between acoustic conditions than objective measures of performance (Schlittmeier et al., 2008). Schlittmeier et al. (2008) suggest *reactive effort enhancement* as a possible mechanism explaining the difference between subjective and cognitive measures. According to Schlittmeier et al. (2008), the subjective awareness of disturbing noise might encourage individuals to invest more effort in the task, leading to reduced effects on performance but heightened experience of disturbance.

This idea is compatible with resource-based frameworks of the behavioural effects of stress (*the cognitive-energetical framework* of Hockey, 1997; *the maximal adaptability model* of Hancock & Warm, 1989). Performance (or stress response) is not only determined by the joint demands posed by the task and an environmental stressor (e.g., noise), but also by the adaptive or compensatory response by an individual (Hancock & Warm, 1989; Szalma & Hancock, 2011). According to Hockey (1997), performance may be maintained under stress by the recruitment of further resources, such as cognitive capacity (e.g., executive control, attention) and mental energy (e.g., effort). However, this is accompanied by behavioural and psychophysiological costs which Hockey (1997) views as latent decrements of performance. Performance is impaired because the buffering adaptive capacity is exceeded (Hancock & Warm, 1989) or because resources are diverted away from the task to the compensatory effort (Szalma & Hancock, 2011). Although the maximal adaptability model has also been applied in explaining the effects of background speech (Szalma & Hancock, 2011), these theories are too general to account for the specific findings related to cognitive disruption by background speech. However, they complement the specific cognitive theories by highlighting the value of using diverse measures in examining performance effects and other outcomes of noise.

1.4.4 Studies on masking sounds

In practice, decreasing speech intelligibility typically involves the use of another sound, i.e., masking sound. Adding another sound makes the abrupt changes in the pitch and level of speech less pronounced. Thus, both the changing-state features of the sound environment and speech intelligibility decrease. Masking sound usually refers to an artificial neutral sound although some naturally occurring sounds, such as babble, may also work as efficient maskers (e.g., Keus van de Poll et al., 2015).

Most of the studies on speech intelligibility have used masking sound as a means of achieving a certain level of speech intelligibility but have not examined the characteristics of the masking sound as such. Typical masking sounds in experiments include white noise (Loewen & Suedfeld, 1992), pink noise (Ellermeier & Hellbrück, 1998) and pink noise filtered to approximately −5 dB/octave (Venetjoki et al., 2006). The latter noise is efficient in masking speech because its spectrum is close to that of speech (Veitch et al., 2002). However, the idea of increasing the sound level to decrease perceived noise is counter-intuitive which may complicate the acceptance of such acoustic solutions at real workplaces. A few of the earliest field studies that compared several masking sounds were unsuccessful in finding any acceptable masking sound (Keighley & Parkin, 1979; Warnock, 1973). More recent laboratory studies suggest that sounds that are most effective in masking speech are not the ones most preferred by people (Schlittmeier & Hellbrück, 2009; Veitch et al., 2002). Thus, the investigation of potential masking sounds is important for the development of masking sound technology. An optimal masking sound should be efficient in decreasing speech intelligibility, it should be perceived as pleasant, or at least as acceptable, and it should not have any obvious negative effects of its own.

A few laboratory studies have tested different masking sounds. Veitch et al. (2002) tested the effects of simulated ventilation noise on acoustic satisfaction and speech masking efficiency by examining different spectra and noise levels. They concluded that an optimum masking sound spectrum should approximately follow the speech spectrum, i.e. a slope of −5 dB per octave increment in the frequency range of 125–8000 Hz. The recommended maximum level of masking sound is approximately 45 dB because higher sound levels increase the risk of annoyance (Bradley, 2003; Veitch et al., 2002).

Music is also a potential masking sound because it is spontaneously used by office workers (Haake, 2011) and may in specific conditions enhance workers' mood and performance (Oldham, Cummings, Mischel, Schmidtke, & Zhou, 1995). Listening to relaxing music may also facilitate recovery after stress-inducing tasks (Khalfa, Dalla Bella, Roy, Peretz, & Lupien, 2003). Schlittmeier and Hellbrück (2009) compared continuous masking sound (pink noise) with legato and staccato music in laboratory conditions, concluding that the two music types were less efficient in reducing the performance effects of office noise than continuous noise. Yet, legato music was preferred to continuous sound by the participants. In recent years[2], natural sounds (DeLoach, Carter, & Braasch, 2015; Keus van de Poll et al., 2015), babble (Keus van de Poll et al., 2015) and other speech-like maskers, such as time-reversed speech (Hioka, Tang, & Wan, 2016; Jiang, Liebl, Leistner, & Yang, 2012) have also been examined as potential masking sounds.

2 These studies were published after the publication of the masking sound experiment (Study II) included in this thesis.

1.5 Issues related to the physical design of office spaces

In order to investigate the cognitive and subjective effects of office noise, it is necessary to have some understanding of the objective acoustic conditions and of the physical factors that affect the transmission of sound inside an office space. A common weakness in field studies on perceived acoustic conditions has been the lack of appropriate physical measurements. This hinders the application of the results to other offices because one cannot be sure what exactly has been investigated. A few field studies have measured office noise levels but found no relation to noise complaints (e.g., Kaarlela-Tuomaala et al., 2009; Nemecek & Grandjean, 1973; Pierrette et al., 2015). This is not surprising, given the evidence on the role of speech intelligibility.

1.5.1 Room acoustic measurement and design

The objective evaluation of office acoustics can focus on room acoustic quality instead of noise exposure. Room acoustics considers how the properties of a room affect sound inside the room whereas building acoustics focus on sound transmission between rooms, or between a building and its environment. Speech intelligibility can be evaluated and affected by room acoustic means in offices.

In open-plan offices, speech intelligibility depends on speech effort (i.e., speech level), sound absorption, screen and furniture height, distance, and masking sound (Bradley, 2003; Keränen, 2015). Typical room acoustic solutions in open-plan offices include the use of sound-absorbing materials on furniture and room surfaces (e.g., ceiling, walls), high screens that block the transmission of sound, and a masking sound system (Keränen, 2015). Together, the absorption and high screens increase the spatial decay rate of speech and other sounds. High spatial decay rate means that noise level is efficiently reduced when the distance to the noise source increases. However, even an efficient reduction of speech level may not be sufficient for decreasing speech intelligibility because intelligibility also depends on the background sound level (Keränen et al., 2012; Virjonen et al., 2007). Masking sound is needed to decrease speech intelligibility because the natural background sound caused by ventilation is usually too low in offices. A masking sound system creates a smooth and neutral background sound from loudspeakers that are evenly placed on the ceiling.

The room acoustic quality of an open-plan office can be measured according to the current international measurement standard for open-plan offices (ISO 3382-3, 2012). In accordance with Hongisto's (2005) model, the standard defines the *distraction distance* (r_D) as the distance from the speaker at which the *STI* falls below 0.50. Beyond the distraction distance speech is assumed non-distracting and, thus, offices with shorter r_D should be acoustically better. Measurements conducted in Finnish offices show considerable variety in r_D between workplaces (Virjonen et al., 2009).

The standard also includes three other room acoustic quantities. The *spatial decay rate of speech* ($D_{2,S}$) describes how much the A-weighted *SPL* of speech reduces when the distance to the speaker is doubled. The A-weighted *SPL of speech at a 4-meter distance* from the speaker ($L_{p,A,S,4m}$) and the average A-weighted *SPL of background noise* ($L_{p,A,B}$) are also measured. $D_{2,S}$ and $L_{p,A,S,4m}$ are related to the attenuation of speech level and mainly depend on the amount of room absorption and screen height (Keränen et al., 2012). Of the ISO 3382-3 quantities, r_D is presumably most directly related to speech intelligibility because it takes into account the combined effect of absorption, screens and the background sound level (Keränen et al., 2012). Thus, r_D is focused on in this thesis.

To date, only a few field studies have examined the relation between r_D and perceived noise. Hongisto and colleagues (Hongisto, 2008; Hongisto, Haapakangas, et al., 2016) have reported a few case studies where a decrease in r_D was associated with a decrease in perceived noise. However, these studies involve methodological weaknesses (small samples, lack of a control group, other simultaneous changes) that restrict the generalisability of the results. The only cross-sectional study (Newsham et al., 2008) that has investigated the relation between a room acoustic measure of speech intelligibility and perceived acoustic conditions did not find evidence for their association. This result may be explained by their measurement method which only considered speech intelligibility between neighbouring workstations. The current view (ISO 3382-3) is that room acoustic measurements should reflect the acoustic quality of the whole office space.

1.5.2 The role of additional quiet workspaces

Another factor that likely affects the perception of acoustic conditions in modern offices is the provision of alternative workspaces, particularly quiet rooms. Possible mechanisms for the subjective benefits of alternative workspaces include a better fit between workspaces and work demands, such as the possibility to use distraction-free spaces for concentration (cf. Duffy, 1997), improved conditions in open-plan workspaces, as some of the distracting activities are moved to other areas (Davis et al., 2011), and an increased perception of control over the environment (Lee & Brand, 2005).

However, there is little evidence to specifically evaluate the benefits of such office features on the perception of the acoustic environment. Studies on modern offices tend to focus more on possible benefits on collaboration and interaction (e.g., Boutellier et al., 2008) even though the ability to work on individual tasks without distractions has equal priority for office employees (Brill & Weidemann, 2001). Office distractions are mentioned as a downside of activity-based offices in descriptive publications (e.g., Bosch-Sijtsema, Ruohomäki, & Vartiainen, 2010; van der Voordt, 2004; Vos & van der Voordt, 2001). These observations are supported by studies comparing activity-based offices with private office rooms (Bodin Danielsson & Bodin, 2009; De Been & Beijer, 2014). However, few studies have compared modern offices with additional workspaces to traditional open-plan offices without such spaces. These studies suggest that workers in non-territorial offices are less disturbed by noise and other environmental factors than workers in open-plan offices (Bodin Danielsson & Bodin, 2009; Kim, Candido, Thomas, & de Dear, 2016) although Bodin Danielsson et al. (2015) only observed this difference among women. These results may indicate that the possibility to switch to a more appropriate workspace decreases perceived noise disturbance, but differences in acoustic satisfaction could also stem from other differences between these office types, such as the increased freedom and flexibility of working in activity-based offices (Blok et al., 2012).

A few studies have investigated the use and perception of workspaces within activity-based offices. Brunia, De Been and van der Voordt (2016) conclude that the provision of enclosed spaces for concentration is one of the most critical factors that differentiates offices with higher satisfaction from less successful cases. Appel-Meulenbroek et al. (2011) report that distractions and privacy are among reasons for choosing a certain type of workspace but note that the need for private workspaces varies substantially between individuals. Both of these studies are descriptive, lacking any statistical testing, which restricts the conclusions that can be drawn from them. Furthermore, some findings from flexible offices suggest that most employees do not prefer to switch workspace actively (Appel-Meulenbroek et al., 2011; Hoendervanger, De Been, Van Yperen, & Albers, 2016). This phenomenon might undermine some of the expected benefits of alternative workspaces on the perceived acoustic environment.

Investigating the benefits of alternative quiet workspaces is important because such spaces can be adopted in various office types. Quiet rooms can be built in existing open-plan offices to enhance possibilities for private discussions and concentration (e.g., Hongisto et al., 2012; Hongisto, Haapakangas, et al., 2016). In such cases, the provision of quiet workspaces is probably not accompanied by major changes in the general way of working, particularly if the number of such rooms is small. In other cases, activity-based and mobile working can be adopted to a higher degree while maintaining personal workstations. Some of such offices may be very similar to flexible offices, both in terms of the office spaces and the working style (De Been & Beijer, 2014). Thus, the versatility of workspaces and the adoption of more flexible, multi-locational working seem to vary along a continuum between traditional open-plan offices and non-territorial flexible offices. The variety between these prototypic office categories and the role of specific design elements, such as quiet workspaces, has not received much attention in the existing literature.

1.6 Gaps in the reviewed literature

The reviewed literature indicates several gaps that this thesis aims to address.

When the research for this thesis started, there was an obvious need for more research on the *STI*-performance relation and Hongisto's (2005) model. The *STI*-performance relation had not been studied in the range where the drop in performance is assumed to occur. The existing research on speech intelligibility was also largely based on the serial recall task with only two exceptions (Schlittmeier et al., 2008; Venetjoki et al., 2006). Examining different tasks was important for several reasons: to gain stronger evidence of the effects of speech intelligibility, to better represent office work and to examine the possibility of a task-specific *STI*-performance relation. These issues have also been addressed by several other researchers parallel to and after the publication of the studies of this thesis (Ebissou et al., 2015; Hongisto, Varjo et al., 2016; Jahncke et al., 2013; Keus van de Poll et al., 2014; Liebl et al., 2016). The evaluation of Hongisto's (2005) model continues to be relevant as the assumptions of the model have since been adopted in the international measurement standard for open-plan offices (ISO 3382-3).

In addition, ecological validity should be improved in laboratory experiments. First, acoustic conditions should be operationalised in a way that links them to real offices. This can be done by using *STI* values that correspond to specific real-life conditions. The ecological validity would be further increased by a realistic manipulation of the *STI* (e.g., by using room acoustic materials) instead of artificial manipulation of sound levels. Such studies have not been previously conducted.

Second, the speech materials and their presentation should better represent office conditions. In open-plan offices, speech is heard from different directions and it alternates with periods of silence. That is, the exposure to background speech is usually neither continuous nor predictable, except in offices where phone conversations are the main work task. Evidence suggests that intermittent background speech is more disruptive than continuous speech (Szalma & Hancock, 2011). Hearing the other side of a phone conversation is an example of such distraction in offices (Emberson, Lupyan, Goldstein, & Spivey, 2010; Jensen & Arens, 2005). However, most speech intelligibility studies have used continuous speech with (Ellermeier & Hellbrück, 1998) or without a plot (Schlittmeier et al., 2008). In addition, speech has usually been produced from one static location (Venetjoki et al., 2006) or without specifying the perceived speech location (Ellermeier & Hellbrück, 1998). Some studies suggests that the performance effect of background speech is modified by the location of speech source, at least in certain tasks (Buchner, Bell, Rothermund, & Wentura, 2008; Spence, Ranson, & Driver, 2000). Many of these limitations also apply to more recent studies (e.g., Jahncke et al., 2013; Liebl et al., 2012; Keus van de Poll et al., 2014). For the conclusions to be valid, the experimental conditions should represent realistic office conditions as closely as possible.

From a practical perspective, it would be very important to examine whether the conclusions based on laboratory studies using the *STI* can be generalised to room acoustic design using r_D. There are several uncertainties related to the link between these parameters. First, the effects of room acoustic design on the *STI* increase with increasing distance (Keränen et al., 2012). The *STI* cannot be decreased efficiently at very short distances in offices without extreme measures (e.g., very high masking sound) which might cause other problems. Due to this restriction, neighbouring workstations are likely located within r_D even in the acoustically best offices, meaning that employees are exposed to intelligible speech from the nearest workstations. It is not known whether this phenomenon abolishes the benefits of room acoustic design which mainly impacts the intelligibility of more remote voices. Second, r_D is a much more inaccurate descriptor of noise exposure in offices than the *STI* is in experimental studies. In laboratory conditions, the *STI* can be determined for the presented background speech. However, r_D does not describe noise exposure but the acoustic properties of the room, assuming one speaker with standardised normal speech effort. The r_D of a room is the same regardless of the presence and activity of the occupants. The shape, size and space-efficiency of an office also affect the number of workstations (i.e., speech sources) within r_D. In addition, the acoustic conditions at individual workstations may deviate from the overall measurement, for example, due to their location in relation to noise sources and noise reflecting surfaces (e.g., a wall). Taken together, it is uncertain whether r_D predicts the perception of acoustic conditions in offices even if such association is supported by more theoretical research on the effects of the *STI*.

An association between r_D and perceived noise would support the use of holistic measures (i.e., the combination of absorption, screens and masking sound) in the room acoustic design of open-plan offices (Keränen & Hongisto, 2013; Keränen et al., 2012). Research is also needed on more specific practical solutions. Investigating the efficiency and acceptability of potential masking sounds is important because workplaces often hesitate their use due to concerns over possible negative effects. The investigation of the benefits of alternative workspaces, particularly quiet rooms, on noise disturbance and other subjective variables is also relevant. Information is needed particularly on their benefits in modern open-plan designs where personal workstations are retained because such offices have not been widely recognised in the international literature but they are currently fairly common in Finland. Researchers should try to identify specific mechanisms or factors that explain the perception of acoustic conditions in modern offices, instead of only examining differences between general office categories which blurs the variety between offices and the role of specific design elements.

Finally, the link between office distractions (such as noise) and other negative outcomes observed in open-plan offices should be investigated with better research designs. Although noise is assumed to contribute to other problems (e.g., Lee et al., 2016; Pierrette et al., 2015), the previous research is mainly based on cross-sectional data. It would be more convincing to show that an increase in perceived office distractions mediates negative changes in other variables in a context of environmental change, such as when workers move from private offices to an open-plan office. Establishing an association between noise and other outcomes, such as employee stress, would suggest that the benefits of reducing noise are not restricted to acoustic satisfaction but may have wider implications for the organization.

2. AIMS OF THE THESIS

The main aim of this thesis is twofold: to investigate problems related to background speech and to examine practical solutions for decreasing those problems. More specifically, this thesis examines how the intelligibility of background speech affects cognitive performance and subjective reactions to the acoustic conditions, and whether these problems can be decreased by workplace design, particularly room acoustic design that decreases speech intelligibility. Speech intelligibility is described with the Speech Transmission Index (*STI*) and the distraction distance (r_D).

The general hypothesis of the thesis is that the negative effects of background speech on performance and subjective reactions decrease with declining speech intelligibility, i.e. the *STI*. Evidence is drawn from both laboratory experiments (Studies I, II and III) and field studies (Studies IV and V). The following research questions are investigated:

Problems:

1. Do office distractions, particularly background speech, impair cognitive performance and subjective perceptions of the work conditions in contemporary open-plan offices? (Studies I-V)

2. Does the *STI* predict the effects of background speech on cognitive performance, and is the observed relation between the *STI* and performance compatible with Hongisto's (2005) model? (Studies I and II)

3. Does the *STI*-performance relation depend on task demands? (Studies I, II, III)

4. Does the *STI* predict subjective reactions to acoustic conditions, including subjective disturbance, acoustic satisfaction and perceived workload? (Studies I, II, III)

5. Does an increase in office distractions, including noise, mediate negative changes in environmental satisfaction, collaboration and stress symptoms following an office relocation? (Study V)

Solutions:

6. How is the use of masking sound (i.e., higher background sound level) perceived? Specifically, is masking sound perceived as disturbing? (Studies I-IV)

7. Are some sound types better as masking sounds than others? That is, do masking sounds differ in cognitive and subjective effects when the *STI* is constant? (Study II)

8. Can the negative effects of background speech be decreased by room acoustic design in realistic conditions where the direction of speech and the distance to the speech sources vary? (Study III)

9. Does the distraction distance (r_D) predict noise disturbance in open-plan offices? (Study IV)

10. Can noise disturbance and related negative outcomes be decreased by providing alternative quiet workspaces at open-plan offices? (Studies IV, V)

3. METHODS

3.1 Laboratory experiments (Studies I, II and III)

3.1.1 Participants

The participants were recruited from local universities. They were native Finnish speakers who reported normal hearing and no dyslexia. Altogether, 189 participants (aged 18-45 years) took part in the experiments (**Table 1**). They were paid a small compensation for their participation. Participants were not allowed to take part in more than one of the experiments.

Table 1. Information on the participants of the laboratory experiments.

	Study I	**Study II**	**Study III**
Total number of participants	37	54	98 (24-25 per condition)
Women / men	24 / 13	21 / 33	73 / 25
Age, *M (SD)*	23.1 (4.4)	25.6 (5.0)	23.9 (4.0)

3.1.2 Research facilities

Studies I, II and III were conducted in simulated office conditions at the Finnish Institute of Occupational Health in Turku, Finland. A smaller office laboratory (30 m^2) with eight workstations was used for Studies I and II (**Figure 2**). The workstations were separated by 1.30 m high screens. For Study III, a larger office space (82 m^2) was constructed in another laboratory (**Figure 2**). This laboratory had twelve workstations. The height and number of screens around workstations were varied according to the experimental manipulations (see Section 3.1.3). In both laboratories, loudspeakers were placed in four corner workstations for the production of background speech while the remaining workstations were used by the participants. Loudspeakers (Genelec 8020) were mounted above the suspended ceiling for the production of masking sound. The loudspeaker systems of the masking sound and speech were separate from each other. The laboratories had a neutral clerical interior design. Acoustic conditions and other indoor environmental factors were monitored during the experiments.

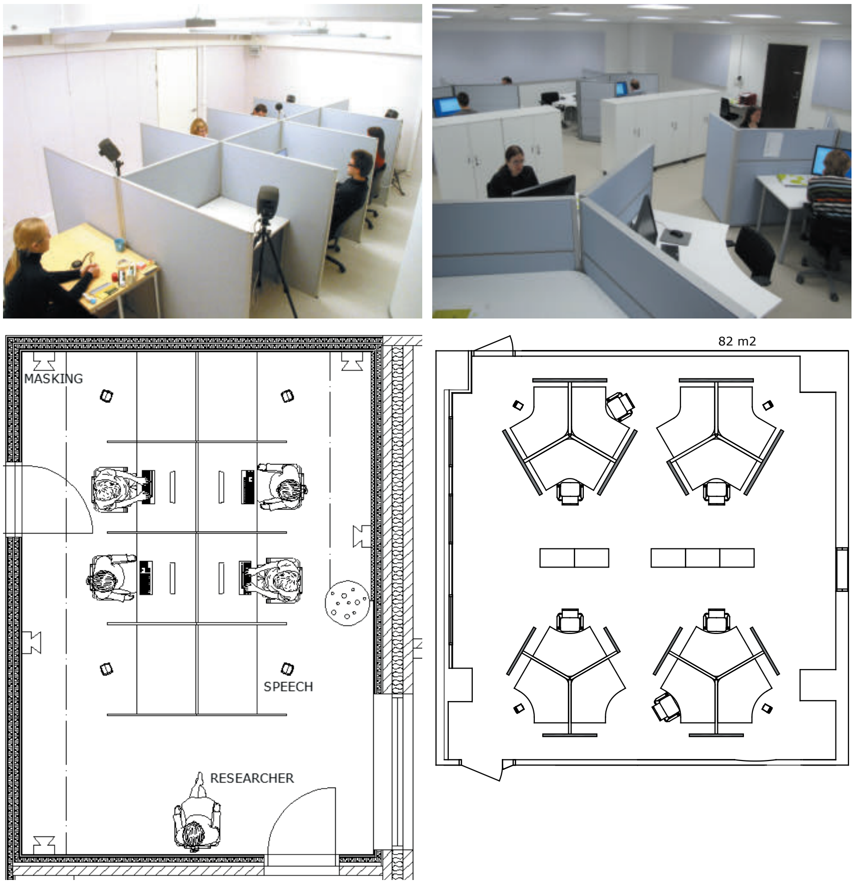

Figure 2. The office laboratories used in Studies I and II (left) and Study III (right). The dimensions of the layout drawings are not comparable. The layout drawing on the right is reprinted from Haapakangas et al. (2014) with permission from Elsevier Ltd.

3.1.3 The design of sound conditions

The main principle in designing sound conditions was to use *STI* values that represent realistic office conditions. The chosen *STI* values of the experiments (**Tables 2 and 3)** correspond to values that can be found between workstations within an open-plan office area (Virjonen et al., 2007; Virjonen et al., 2009). An *STI* of approximately 0.65 was used to represent poorly designed open-plan offices where speech intelligibility between workstations is high. An *STI* of 0.35 to 0.40 represents an open-plan office with very good acoustic design where speech intelligibility is significantly lowered. Reference conditions represent the absence of speech (*STI* 0.00, Study II) or very low speech intelligibility (*STI* 0.10, Study I).

In Studies I and II, the overall sound level was kept constant at approximately 48 dBA except for the silent condition in Study II. The manipulation of the *STI* was done by changing the levels of speech and masking (i.e., the speech-to-noise ratio) manually. The used speech levels varied between 39 and 48 dB which correspond to realistic speech levels heard in a neighbouring workstation in different acoustic conditions (Virjonen et al., 2007). The range of the background sound level was 38 to 48 dBA in Study I, and 38 to 46 dBA in Study II. The lowest value (38 dBA) resulted from ventilation noise in the absence of additional masking sound. The recommended maximum level for masking sound is 45 dB (Bradley, 2003; Veitch et al., 2002). In Study I, masking sound was produced at the higher level of 48 dB in one condition (*STI* 0.10). This compromise was done to maintain background speech at a realistic level while keeping the overall noise level constant across conditions. Each condition lasted for approximately 45 minutes in Study I and 25 minutes in Study II.

Table 2. Description of the STI values used in Studies I and II.

STI	**Corresponding office conditions**
0.00	Condition where speech is absent, e.g. private office room with excellent sound proofing or an open-plan office with a silent behavioural code.
0.10	Private office room with the door closed. Speech intelligibility is extremely low.
0.35-0.40	Open-plan office with high speech privacy and very good room acoustic design.
0.62-0.65	Open-plan office with low speech privacy and poor room acoustic design.

In Study III, the manipulation of the *STI* was done in realistic ways by building three different acoustic conditions in the office laboratory. The changes involved the use of absorption materials on the room surfaces and screens, the screen height, the number of screens around workstations, and the use of masking sound. The conditions were created using only products that are commercially available to ensure that the experimental conditions were realistic. The conditions varied from a poor acoustic environment, which lacked both absorption materials and the masking sound (*noAbs_noMask*), to an optimum condition including both maximum attenuation (i.e., absorption, higher screens, increased enclosure) and masking sound (*Abs_Mask*). A condition with maximum attenuation but no masking sound was also included (*Abs_noMask*). A quiet condition was included as the fourth condition to present a situation without background speech. The conditions are described in more detail in **Table 3**. The level of speech was constant in all conditions (except in the quiet control condition). Thus, changes in speech intelligibility solely depended on the room acoustic changes. The speech level was 53 dB at one meter distance. This level is slightly lower than the standardised level of normal speech effort (57.4 dB; ISO 3382-3) because evidence suggests that workers naturally lower their voice in open-plan offices (Warnock & Chu, 2002). The background sound level varied from 33 to 45 dBA, depending on the condition (**Table 3**). Unlike in Studies I and II, the distance between participant workstations and speech loudspeakers varied from 2 to 6 meters due to the bigger room. Thus, the *STI* of speech varied within an experimental condition as it would also vary in an open-plan office. The *STI* values of each condition were determined in the nearest workstation (2 meters) and the most remote workstation (6 meters). The range of the *STI* values within each condition is presented in **Table 3**. Within each condition, tasks were performed in three consecutive blocks lasting for 40, 60 and 60 minutes.

Table 3. The description of the room acoustic conditions in Study III.

	Acoustic condition			
	noAbs_noMask	***Abs_noMask***	***Abs_Mask***	***Quiet***
General description	Poor conditions; no attenuation nor masking sound	Maximum attenuation, no masking sound	Maximum attenuation with masking sound	No background speech
Treatment of the room				
Background speech	On	On	On	Off
Absorption installed on the ceiling	No	Yes	Yes	No
Absorption installed on walls	No	Yes	Yes	No
Screen absorption installed	No	Yes	Yes	No
Screen height (m)	1.3	1.7	1.7	1.3
Side screens installed	No	Yes	Yes	No
Masking sound level (dBA)	37	33	45	35
Room acoustic conditions				
STI of speech in the nearest workstation (2 meters distance)	0.70	0.80	0.51	0.00
STI of speech in the most remote workstation (6 meters distance)	0.60	0.42	0.11	0.00

In all studies, the exact *STI* values of the prevailing acoustic conditions were determined by acoustic measurements before running the experiments. The *STI* in the participants' workstations was measured using winMLS-software. The *STI* was calculated from the measurements of the *SPL* of speech, the *SPL* of background sound and the early decay time using modulation transfer functions, as described for example by Hongisto et al. (2004).

In Study III, the conditions were also measured using the ISO 3382-3 standard (see Section 3.2.5). The main difference between these measurements concerns the speech level used in determining the *STI*. In the ISO 3382-3 measurements, standardised normal effort speech (57.4 dB) was used, whereas the primary measurements of the *STI* used the actual speech levels produced by the loudspeakers during the experiment. The ISO measurements were included because they enable the comparison of the conditions to real offices measured using the same standard.

3.1.4 The creation of speech materials

The purpose in designing speech materials was to simulate an office environment where speech is heard from different directions and alternates with silence arbitrarily. Only one voice was heard at a time to represent a 'worst case scenario' where speech is not masked by simultaneous speakers. Using only one speaker at a time is also consistent with the idea behind the measurement standard (ISO 3382-3) for open-plan offices.

All speech recordings were edited from radio programmes obtained from YLE (the Finnish Broadcasting Company). The materials for Studies I and II were based on the same eight radio programmes whereas new material was obtained for Study III.

In Studies I and II, the speech recordings were created from neutral and calm interview programmes. The speech was cut into 10-to-30-second-long full-sentenced samples in which only one person was talking. There was a 3.2-8.8-second silence between each sample. The speech levels were normalised between speech samples in Study II but differences in speech spectrum between speakers were not modified in either study. The successive samples were taken from different programs so that there was no plot to follow. The final recording, in which speech and silence alternated, was stored randomly on four channels of a hard disc recorder (Alesis adat HD24) and distributed on four separate loudspeaker channels. Several recordings were created to meet the requirements of the experimental design (i.e., three 45-minute-long recordings for Study I and six 25-minute-long recordings for Study II).

The speech material was re-designed for Study III to represent more distracting and lively conversations. The recordings were also cut to represent one side of a conversation (e.g., a phone call) because such background speech appears to be particularly distracting in open-plan offices (Emberson et al., 2010; Jensen & Arens, 2005). Thus, the voice and the topic remained the same in each of the workstations where the loudspeakers for background speech were located. New material from friendly debates was used for the recordings. The speech of each participant was isolated from each program and placed to one channel of a four-channel sound file.

The speech material of a single speaker (i.e., each channel) was cut to separate 5-to-25-second-long sentences. The four-channel speech file was then expanded and arranged to remove any overlap between the channels. The sound levels of the sentences were individually adjusted to the same A-weighted level (53.0 dB) to correct for variations in speech effort. In addition, the spectrum of each speaker was modified so that the octave band levels deviated from the speech spectrum shape of ISO 3382-3 by less than 3 dB. A 1-to-8-second break was placed between the speech sentences when a switch to another corner (i.e., channel) took place. The order of the channels was pseudo-randomised so that one speaker was not active twice in succession and the total amount of speech from every channel was equal. Adobe Audition 3.0 software was used for editing. The length of the final four-channel playback recording was 181 minutes. Only one recording was needed due to the between-participants manipulation of the acoustic condition.

3.1.5 Masking sounds

The spectrum of masking sounds was selected as a compromise between efficient speech masking and subjective comfort based on the results of Veitch et al. (2002). It was approximately -5 dB/octave slope within octave bands 125–4000 Hz in Studies II and III, but closer to -4dB /octave slope in Study I (see **Figure 3**).

Filtered pink noise was used as a masking sound in all experiments. Additional sound types were chosen for Study II. Spring water sound was used to represent a natural sound because its spectrum was close to the masking sound spectrum recommended by Veitch et al. (2002), unlike the spectra of many other natural sounds. Music was selected because it is spontaneously used by workers in different work settings. Both vocal music (i.e., music with lyrics) and instrumental music were used to gain information on the role of verbal content in music. Ventilation sound was selected because it is the most common environmental sound in buildings. Filtered pink noise was chosen because it is frequently used in commercial masking sound systems. The masking sounds were obtained from live recordings (ventilation noise and spring water sound), commercial audio tracks (instrumental and vocal music) and digital sources (filtered pink noise).

Masking sound was produced in real-time by pink noise generators in Studies I and III. In Study II, masking sounds were stored on CDs which were played during the experiments (Marantz CD4000). In all experiments, masking sounds were produced from loudspeakers that were mounted above the suspended ceiling. Each of the masking loudspeakers had an independent filter (Yamaha DME24N) to obtain an equal frequency response at each workstation.

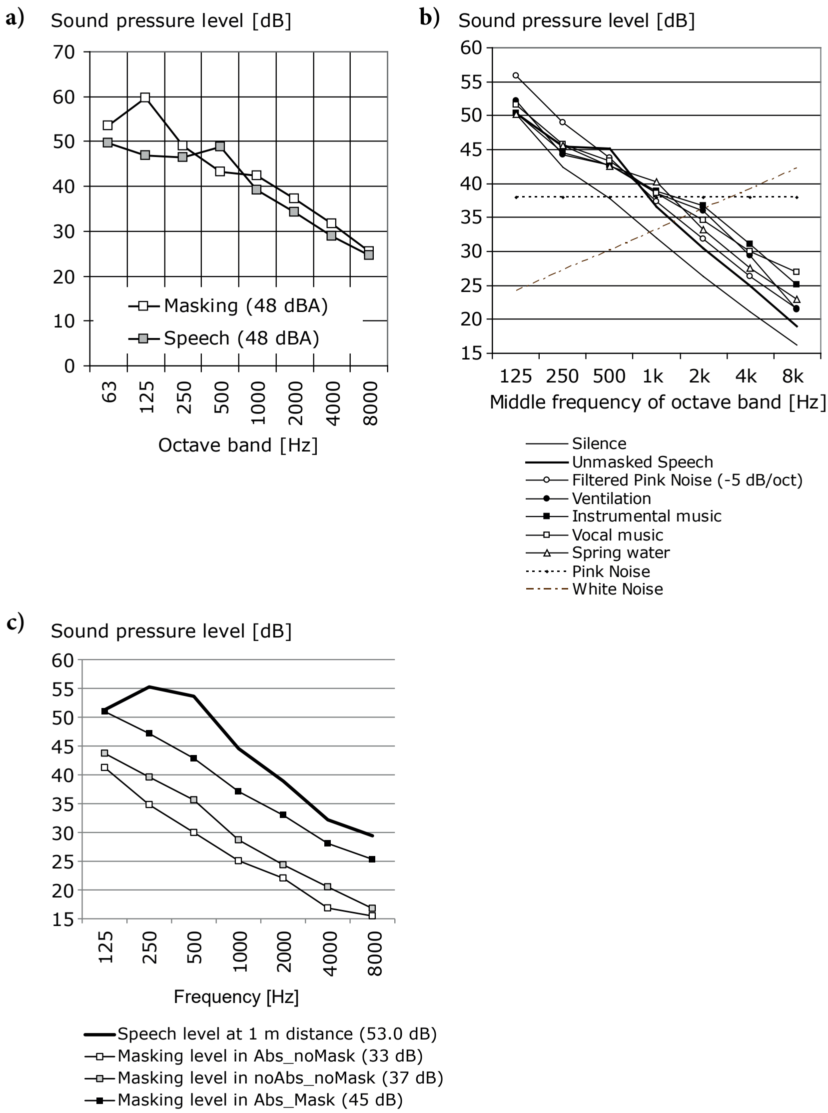

Figure 3. The spectra for the speech and masking sounds in a) Study I, b) Study II, and c) Study III. Pink noise and white noise are shown in Figure 3b to demonstrate the difference to the filtered masking sounds used in these experiments. Figure 3c is reprinted from Haapakangas et al. (2014) with permission from Elsevier Ltd.

3.1.6 Cognitive tasks

The aim of the task selection was to improve the methodology of previous research in terms of ecological validity and task variety.

Most of the previous research has been based on the *serial recall* task which is a classic measure of short-term memory. Short-term memory is viewed as a central component of the human information processing system and is assumed to be involved in many mental activities (e.g., Gathercole & Baddeley, 1993). Thus, researchers (e.g., Jahncke et al., 2011; Liebl et al., 2012; Schlittmeier & Hellbrück, 2009) have argued that the effects of background speech on basic memory processes could be generalised, to some extent, to more complex every-day tasks that require these processes.

However, serial recall is a simple span task that only taps into short-term memory storage (Daneman & Carpenter, 1980). The concept of working memory (WM) considers both the storage and the processing capacity of short-term memory. In *complex span tasks*, participants are required recall a list of items (e.g., words) while also performing a secondary processing task, such as mathematical equations (Redick & Lindsey, 2013). Performance in such tasks predicts higher-order cognitive abilities, such as language comprehension (Daneman & Merikle, 1996) and fluid intelligence (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Unsworth, Redick, Heitz, Broadway, & Engle, 2009) although there is conflicting evidence whether the complex tasks predict these abilities better than simple measures of short-term memory (e.g., Colom et al., 2008; Daneman & Merikle, 1996; Unsworth & Engle, 2007).

Memory updating tasks, such as the *N-back task* (Owen, McMillan, Laird, & Bullmore, 2005), represent another approach to working memory that is frequently used in cognitive neuroscience (Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2009). In the N-back task, participants are presented items (e.g., letters) in a sequence. For each item, the participant has to decide whether it matches the one presented *n* items ago. Thus, participants are required to maintain and continuously update items in memory. The psychometric properties of N-back have been researched less than those of complex span tasks, but N-back has similarly been associated with fluid intelligence (Kane, Conway, Miura, & Colflesh, 2007). Although the complex span and N-back tasks bare some similarity, they are weakly correlated and appear to measure different processes of working memory (Redick & Lindsey, 2013).

Based on this evidence, both types of working memory tasks were used in this thesis: an operation span task (Turner & Engle, 1989) and the N-back task (e.g., Owen et al., 2005). Serial recall was included in all experiments to enable comparison with previous studies. In addition, a *visuo-spatial serial memory task* (e.g., Parmentier, Elford, & Maybery, 2005) was used in Study I to examine non-verbal serial memory which has also been shown to be susceptible to background speech (Jones, Farrand, Stuart, & Morris, 1995). All these tasks involve some degree of serial processing although the working memory tasks are more complex.

It was also important to include more complex tasks that bare more resemblance to real office work. *Reading comprehension, text memory, proofreading* and *creative thinking* were used as such tasks. All of these tasks require some degree of semantic processing and might, thus, be affected by background speech due to semantic interference. It should be noted that semantic processing is referred to here on a general level, but should not be understood as a unitary phenomenon. For example, the semantic processes required in the expansion of conceptual ideas in the creative thinking task are quite different from those required in the extraction of meaning from a written text. All of these tasks also require a combination of different cognitive processes, that is, they are not purely 'semantic tasks'.

The operation span task was also used as a measure for *working memory capacity* in Study III. It was included as a covariate to account for individual differences in cognitive ability because the acoustic conditions were manipulated between groups in Study III.

The tasks are summarised in **Table 4**. Detailed task descriptions are given in the original publications.

Table 4. Summary of the tasks used in Studies I, II and III.

Task	Essential cognitive processes	Presentation	Study	Reference
Serial recall	Verbal short-term memory, particularly storage and memory for order	computer	I, II, III	E.g., Jones & Macken, 1995; Schlittmeier et al., 2008
Operation span	Verbal working memory (storage and processing)	computer	I, III	Turner & Engle, 1989
N-back	Working memory (online monitoring and updating)	computer	III	Owen et al., 2005
Dot series task	Visuo-spatial short-term memory, memory for order	computer	I	Parmentier et al., 2005
Reading comprehension	Four components, including text recall, inferences, integration with prior knowledge and activation of long-term memory	computer	I	Hannon & Daneman, 2001
Proofreading	Orthographic and semantic processing	pen and paper	I, II	Venetjoki et al., 2006
Creative thinking	Generation of new ideas (ideational fluency and originality)	pen and paper	II	Wyon, 1996; Guildford, Christensen, Merrifield, & Wilson, 1978
Text memory	Long-term memory, learning and recall	paper (reading), computer (recall)	III	Kaakinen, Hyönä & Keenan, 2003[1]

[1]The test procedure was designed by the authors of Study III, but the texts were from Kaakinen et al., 2003.

3.1.7 Questionnaires

Questionnaires were used in all experiments to gather background information and to assess subjective reactions to the sound conditions and perceived effects on performance. The content of the questionnaire had some differences between the studies due to different research needs and questionnaire development. The questions were mostly rated on a 5-point scale (1 = not at all, 5 = very much).

In all studies, subjective disturbance (or acoustic satisfaction in Study II) included questions on the perceived pleasantness and disturbance of the sound environment, attentional capture and perceived habituation to the sound environment. In Study I, a composite variable for *subjective disturbance* included five questions. In addition, self-rated task difficulty was assessed with one question immediately after each task. A wider questionnaire with 16 items was developed for Study II where the investigation of acoustic satisfaction was more important. Composite variables were formed for *acoustic satisfaction* (12 items) and *subjective workload* (4 items). In Study III, *perceived disturbance* with 4 items was used in the analyses. The *NASA Task Load Index* (NASA-TLX; Hart & Staveland, 1988) was used in Study III for the assessment of subjective workload on six scales (mental, physical, and temporal demand, performance, effort, and frustration). Responses from 1 to 100 were given on a slider bar.

In each experiment, the disturbance of different sounds was also separately rated, including background speech, the masking sound and the sounds made by other participants. The purpose was to monitor the possible disturbance caused by the masking sound and to verify that acoustic disturbance was related to the manipulation of background speech, and not some other sound.

Noise sensitivity was included in Study III. It was assessed with a four-item version (Griefahn, Marks, & Schreckenberg, unpublished) of the subscale 'work' in NoiSeQ (Schutte, Marks, Wenning, & Griefahn, 2007).

3.2 Field studies (IV and V)

3.2.1 Overview of the field studies

Study IV examines the relation between room acoustic quantities, including r_D, and perceived noise disturbance in a sample of 21 open-plan offices. The data included room acoustic measurements according to the ISO 3382-3 standard and acoustic surveys. The data were combined from several case studies and synthesised using individual participant data meta-analysis (Debray et al., 2015).

Study V compares two organizations that moved from private offices to modern open-plan offices. The room acoustic conditions of the open-plan offices were very similar, but the offices differed in the number and variety of quiet workspaces. Thus, this study demonstrates that there are other factors that influence the perception of office noise in addition to the room acoustic conditions, focusing particularly on the role of quiet workspaces. The study involved a quasi-experimental analysis (i.e., before-after comparisons within organizations, and comparisons between organizations) of the perceived office distractions, environmental satisfaction, collaboration and stress symptoms. Mediation analyses were conducted to examine distractions as a possible mediator for negative changes observed in other outcome variables. A serial mediation model for the negative effects of the office relocation on stress symptoms was also tested, with distractions as the first and collaboration as the second mediator. Collaboration was considered as a possible mediator because open-plan offices have been associated with interpersonal problems (e.g., Bodin Danielsson et al., 2015; De Croon et al., 2005) and because the quality of interpersonal relationships is, in turn, associated with different psychological symptoms (Stansfeld & Candy, 2006). In addition, associations between the perception of alternative workspaces and the key outcome variables were investigated to gain more information on the role of quiet workspaces.

The data in both studies were originally gathered for another purpose and the use and analysis of the data were retrospectively designed. The data of Study IV consists of separate case studies conducted by Finnish Institute of Occupational Health between 2002 and 2014. Data were mostly gathered in different research projects but also in acoustic consultation services. In cases where the use of data for research purposes had not been previously agreed upon, written consents were requested and received from the workplaces for the use of data in Study IV. The data of Study V were initially gathered in response to the request of two organizations to monitor an environmental change, independent of each other. The respondents were informed that the data could be used for scientific research. The organizations later gave written consents for the use of data in Study V.

3.2.2 Participating organizations and respondents

Study IV included data from 21 open-plan offices and from altogether 883 respondents (see **Table 5**). The data originate from different research designs (see the original publication). In 15 studies with repeated measures data (i.e., before-after designs involving a change in the office environment), the first measurement conducted in an open-plan office was included in the meta-analysis. In one case, the second measurement was used because the first survey was retrospective, i.e. the respondents were evaluating an open-plan office in which they no longer worked. Study IV included the data that were gathered in open-plan offices after the office relocation in Study V.

Table 5. Descriptive statistics for the samples used in Study IV.

Sample characteristic	Complete sample	Activity-based offices excluded
Offices, *N*	21	17
Respondents, *N*	883	667
Age, *M* (*SD*)	42.1 (11.2)	41.4 (11.2)
Age, range	20 - 67	20 – 67
Gender, % female	55.8	57.6

Study V involved two workplaces from the Finnish public sector. Organization A belongs to a ministry of the government and works with the development of policies, public administration and legislation in its field of expertise. Organization B provides information services, such as data registers, for public authorities and companies. The environmental changes involved approximately 190 employees in Organization A and 130 in Organization B. Data were gathered twice: before (Time 1) and after (Time 2) the office relocation. The timing of the data gathering differed between the organizations but there were at least eight months between the surveys and the actual office change. The respondents who worked in a private office room at Time 1 (n=65 in Organization A, n=64 in Organization B) and in open-plan workspace at Time 2 (n=135 in A, n=71 in B) were included in the study. Descriptive statistics for the respondents are shown in **Table 6**. Of these samples, 42 respondents in Organization A and 49 respondents in Organization B returned both surveys and were used in the within-subjects analyses of the data.

Table 6. Descriptive statistics for the respondents included in Study V.

Characteristic	Organization A		Organization B	
	Time 1	**Time 2**	**Time 1**	**Time 2**
N	65	135	64	71
Age, *M* (*SD*)	50.2 (10.1)	46.6 (10.3)	51.0 (10.3)	50.9 (10.8)
Age, range	27-67	22-65	28-65	30-67
Gender, % female	70.8	61.5	62.5	62.9
Education, % bachelor's degree or higher	87.7	89.7	63.4	65.8
Service in the organization, years, *M* (*SD*)	13.1 (11.7)	9.9 (9.6)	19.2 (13.6)	17.4 (13.1)
In supervisory position, %	15.4	11.3	23.1	20
Response rate, %	52	74	59	65

3.2.3 Office descriptions

All open-plan offices included in Studies IV and V had personal workstations. In Study IV, the open-plan offices were heterogeneous. Call-centres and similar workplaces with constant babble were excluded from the study due to their specific acoustic environment. Open-plan offices were defined as workspaces of six or more occupants. It was important to recognise open-plan offices with a more activity-based way of working because any benefits rising from this office concept might have distorted the relation between the room acoustic measurements and perceived noise disturbance. Ideally, the degree of activity-based workspace switching could have been included as a variable in the analysis but most open-plan offices lacked these features (and questions assessing them). Thus, only the offices where the use of alternative workspaces was regular among the majority of workers and where the work was more mobile (i.e., the majority of workers worked weekly outside the office, e.g., at home), were considered as activity-based offices. The categorization was based on questionnaire information but also on observations made during visits to these offices. Study IV did not specifically analyse the relation between room acoustic conditions and perceived noise in activity-based offices due to their low number. Activity-based offices were only identified so that any bias caused by them could be checked.

In Study V, most workers had private office rooms before the office change. A minority of workers in other types of office spaces were excluded from the study. In both organizations, the workers moved to renovated office spaces. The new offices can generally be described as modern open-plan offices due to the lack of an appropriate internationally recognised definition. Both organizations would be considered as multi-space offices in Finland because they included a combination of open-plan work areas and alternative workspaces. The office of Organization A combined the concept of activity-based working with the use of personal workstations and is, thus, somewhat similar to the Dutch definition of combi-offices (e.g., De Been & Beijer, 2014; Vos & van der Voordt, 2001). In Organization A, more flexible working was encouraged and the ICT and management were developed to support this during the study. However, the work cannot be considered mobile as most of the working time was spent at the office, at one's workstation. The office of Organization B was closer to a typical open-plan office but included some alternative workspaces. Remote working was increased during the office change but, overall, the developments in the way of working appeared smaller than in Organization A. The focus of Study V is not on particular office categories but on the role of specific design elements (namely, the quiet workspaces) which can be incorporated into different office designs.

The essential difference between the open-plan offices of Study V was the number and variety of alternative quiet workspaces, and their distance to the open-plan areas (see

Figure 4). The office of Organization A included several non-assigned workspaces for quiet work near each open-plan office on each of six floors. The design of these workspaces varied, including workspaces of one, two and four users and phone booths on each floor, and a creative space with more casual interior design that was shared by the workers of all floors. The ratio of the number of workstations in quiet rooms to the number of employees was 0.40. The activity-based office of Organization B included only one workspace for quiet work which had workstations for eight users. This workspace was located at one end of the building and was meant to be used by all employees who were located on two floors (**Figure 4**). The ratio between the number of quiet workstations and employees was 0.07. Space-efficiency was substantially higher in Organization B. Employees in both offices had personal workstations in open workspaces, shared by 4 to 26 workers. The number of formal meeting rooms (for over 6 people) declined in both organizations after the office change, but the number of smaller meeting rooms increased. In both organizations, employees were allowed to personalise their workstations before and after the office change. More details on the office spaces can be found in the original manuscript.

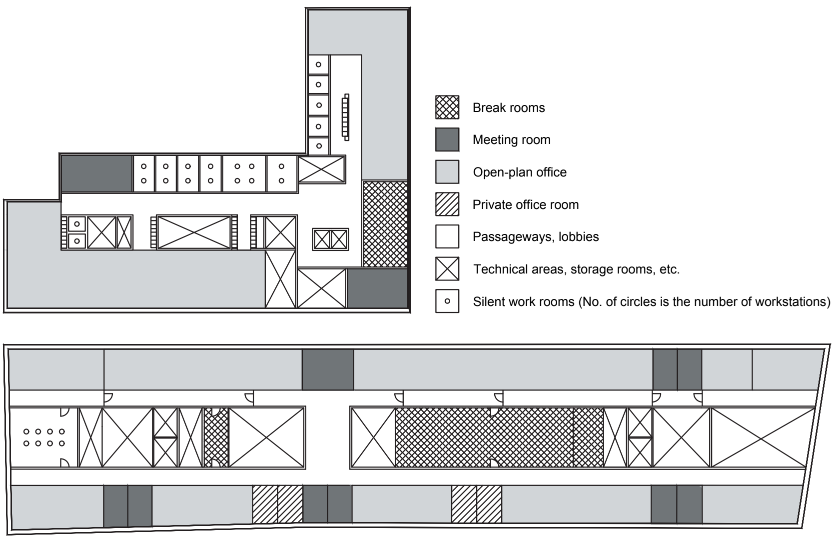

Figure 4. Floor plans of Organizations A (above) and B (below) after the relocation (Time 2). The floor plans represent one of several floors. Mutual dimensions are in scale.

3.2.4 Questionnaires

In Study IV, the original questionnaires differed in content and length. Two measures were used for this study: disturbance by noise in general and disturbance by background speech. Both items were measured on a 5-point scale (1 = Not at all, 5 = Very much).

Disturbance by noise in general assessed the recent perception of disturbing noise at the respondent's workstation. Disturbance caused by background speech was formed from a variety of questions. At each workplace, two to three sources of speech that were relevant to the given workplace were assessed, such as speech from neighbouring workstations and speech from shared facilities. The listed sources varied in different surveys depending on which sources were present at the workplaces. A variable for disturbance by speech was constructed by taking the highest rating given by an individual to any of the speech sources as this was assumed to reflect the main source of disturbing background speech. Age and gender were also included in the analyses.

The original surveys of Study V covered several themes, including demographic data, work demands, mobility and multi-locational working, indoor environment, noise sources, visual and acoustic privacy, decoration, psychosocial environment, symptoms, use and perceptions of the office spaces and perceptions of the office change. Many of the questions were the same as used by Hongisto et al. (2016). As the studies were initially conducted independently of each other, the surveys differed slightly between the organizations. Most questions were rated on a 5-point scale.

The key outcome variables of the study were *distractions* (6 items; Cronbach's α: 0.76-0.9[3]), *collaboration* (3 items; Cronbach's α: 0.77-0.88), s*tress symptoms* (4 items; Cronbach's α: 0.70-0.87) and *environmental satisfaction* (one item, 1 = Not at all satisfied, 7 = Very satisfied). The composite variables were formed by using principal component analysis with an oblique promax rotation. The items included in the composite variables are shown in **Table 7**. Noise could not be examined as a separate variable because it was loaded on the same factor with other distractions and items related to privacy. However, the composite variable 'distractions' correlated strongly with overall noise disturbance (*r*= 0.87-0.90) and distraction caused by speech from nearby workstations (*r*=0.73-0.79).

In addition, several individual items measuring the use of alternative workspaces, satisfaction with them, work characteristics, and multi-locational working were analysed (see the original manuscript).

3.2.5 Room acoustic measurements

The room acoustic properties of the open-plan offices in Studies IV and V were measured according to the ISO 3382-3 standard. The standard did not exist when most of the offices in Study IV were investigated but the measurement method had been developed. The method was first published by Hongisto, Virjonen, and Keränen (2007) and later in detail by Virjonen et al. (2009).

3 Cronbach's α's were calculated separately for both surveys (Time 1 and Time 2) and both organizations.

The basic idea of the method is to measure the *SPL* and *STI* of normal-effort speech at the workstations at various distances from the sound source which is positioned at one workstation. The measurement signal of the sound source (loud pink noise) was produced using an omnidirectional loudspeaker. The *STI* was determined at each workstation based on the *SPL* of speech and the early decay time between the source and the receiver, and the *SPL* of background noise. The measurement of the background noise level excluded the activity noise but included the steady-state sounds of the building, mainly caused by ventilation or a sound masking system. The room was always unoccupied during the measurements, as stated in the ISO 3382-3 standard.

Table 7. The composite variables used in Study V.

Variable	Included items	Question	Scale
Distractions	Noise, sound conditions	A	a
	Lack of speech privacy	A	a
	Feeling that there are too many people occupying the space	A	a
	Movements in the field of vision (such as other people)	A	a
	There are many distractions here.	B	b
	I have sufficient privacy for working.[1]	B	b
Collaboration	The atmosphere is nice and relaxed here.	B	b
	It is easy to contact one's colleagues in this environment.	B	b
	The workplace is characterised by a cooperative spirit.	B	b
Stress symptoms	Tiredness	C	c
	Headache	C	c
	Problems with motivation	C	c
	Problems with concentration	C	c

A: How much have you been negatively affected by the following work environmental factors at your workstation recently?
B: How do you view the following statements concerning your work environment?
C: How often have you experienced any of the following symptoms or feelings recently?
a: 1 Not at all, 2 Only slightly, 3 To some extent, 4 To a great extent, 5 To a very great extent
b: 1 Strongly disagree, 2 More of less disagree, 3 Neither agree nor disagree, 4 More or less agree, 5 Strongly agree
c: 1 Never, 2 Only rarely, 3 Occasionally, 4 Often, 5 Very often
[1]Reverse-scored

3.3 Statistical analyses

In Study I, the data from most cognitive tasks were analysed with one-way repeated measures ANOVAs with three levels (STI 0.10, 0.35 and 0.65). Due to non-normal distributions, the reading comprehension task and the questionnaire measures were analysed using Friedman's Test, followed by Wilcoxon's test for paired comparisons. Bonferroni adjustments were made to paired comparisons between conditions.

In Study II, the serial recall and creative thinking tasks were analysed using a mixed 7 × 2 ANOVA with seven sound conditions as a within-participant variable and the presentation order of the tasks as a between-participants factor (two orders were used). The proofreading task was analysed using a mixed 7 × 2 × 2 ANOVA with seven sound conditions and two error types as within-participant factors, and the presentation order as a between-participants factor. Repeated measures ANOVAs were used for the questionnaire items that were normally distributed and Friedman's test for the variables that were not. Paired comparisons were performed using t-tests or the Wilcoxon Signed Rank test. Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995; Benjamini & Yekutieli, 2001) was used for alpha-error adjustments in paired comparisons.

In Study III, the serial recall and operation span task were analysed with 4 (acoustic condition) X 3 (test block) x 2 (noise sensitivity group based on a median split) ANCOVAs with working memory capacity as a continuous covariate. The acoustic condition and noise sensitivity were between-participants factors. The test block was a within-participant factor indicating exposure time because the tasks were repeated in three blocks (40, 60 and 60 minutes) to assess possible interactions between exposure time and performance. The text memory task was performed only once and analysed with a 4 (acoustic condition) x 2 (noise sensitivity) ANCOVA with working memory capacity as a covariate. The reaction times (RTs) in the N-back task were analysed with a mixed 4 (acoustic condition) x 3 (test block) x 3 (N-back level of difficulty) x 2 (noise sensitivity) ANOVA, in which acoustic condition and noise sensitivity were between-participants variables. Working memory capacity was not included because it did not have a linear relation with the RTs. The total scores and the subscales of the NASA-TLX were analysed with mixed 4 (acoustic condition) x 3 (test block) x 2 (noise sensitivity) ANOVAs in the short-term memory and working memory tasks, and with a 4 (acoustic condition) x 2 (noise sensitivity) ANOVA in the text memory task. The other questionnaire items were analysed with the non-parametric Kruskal-Wallis test, followed by Mann-Whitney U tests for paired comparisons. Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995; Benjamini & Yekutieli, 2001) was used for alpha-error adjustments in paired comparisons.

In Study IV, the original 5-category items (disturbance by noise in general and disturbance by background speech) were coded into two categories by combining the lowest three and highest two values (0 = low disturbance, 1 = high disturbance). The distraction distance (r_{D}), the spatial decay rate of speech ($D_{2,\mathrm{S}}$), the speech level at 4 meters from the speaker ($L_{p,\mathrm{A,S,4m}}$) and the average background noise level ($L_{p,\mathrm{A,B}}$) were examined as predictor variables. A one-stage meta-analysis of individual participant data (Debray et al., 2015) was conducted using two-level logistic regression with respondents nested in workplaces (i.e., offices). The room acoustic predictors were workplace level variables. The models were fitted with a random intercept for workplace and fixed effects of the room acoustic predictor, age and gender. Analyses were conducted with two samples: the complete sample (21 offices) and a sample excluding activity-based offices (17 offices).

In Study V, principal component analysis with an oblique promax rotation was used for forming composite variables. The non-parametric Wilcoxon Signed Rank Test was used for within-participants comparisons to examine changes in the key outcome variables between Time 1 and Time 2. Between-participants comparisons were carried out to compare the organizations at Time 1 and Time 2 (Mann-Whitney U test), and to examine differences in the perception of the alternative workspaces between sub-groups at Time 2 (Kruskal-Wallis Test). Bonferroni corrections were applied to the paired comparisons of multiple groups. For the mediation analyses, a path-analytic approach was applied using ordinary least squares regression as illustrated by Montoya and Hayes (2016). Bias-corrected bootstrap 95% confidence intervals for indirect effects were generated using 5,000 bootstrap samples. The tested mediation models are shown in **Figure 5**.

The statistical analyses were conducted with IBM SPSS Statistics versions 16.0, 20.0 and 23 (Armonk, NY: IBM Corp) in Studies I, II, III and V. In Study IV, the data were analysed with R (version 3.2.2, R Core Team, 2015) using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015). The mediation analyses in Study V were performed using the MEMORE macro for SPSS developed by Montoya and Hayes (2016).

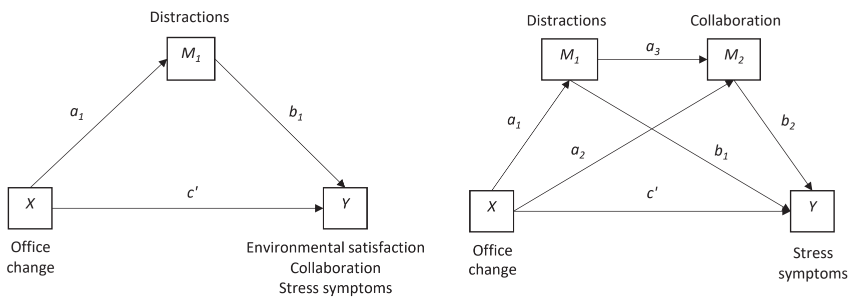

Figure 5. A simple mediation model (left) and a serial mediation model with two mediators and three mediated paths (right). The models test indirect path(s) for the effect of office change (X) on the outcome variable (Y) through a change in the mediator(s) (M). c'= direct effect, controlling for the mediator(s).

4. OVERVIEW OF THE EMPIRICAL STUDIES

4.1 STUDY I

Haka, M., Haapakangas, A., Keränen, J., Hakala, J., Keskinen, E., & Hongisto, V. (2009). Performance effects and subjective disturbance of speech in acoustically different office types - a laboratory experiment. *Indoor Air, 19*(6), 454-467.

The aim of this study was to examine whether speech intelligibility, determined by the *STI*, predicts the effects of background speech on cognitive performance and subjective disturbance. A secondary aim was to investigate whether the relation between the *STI* and performance depends on the task requirements. Three sound conditions with different *STI* values were tested: *STI* 0.10, *STI* 0.35 and *STI* 0.65. Sound condition was manipulated within participants. The participants performed five tasks in each condition: serial recall, a verbal working memory task (operation span), a visuo-spatial serial memory task, a proofreading task and a reading comprehension task. Perceived task-difficulty was rated immediately after each task. At the end of each condition, the participants filled in a questionnaire on the subjective perceptions of the sound condition and the specific disturbance caused by background speech and masking sound.

The results showed that the *STI* of background speech affected performance in the verbal short-term memory and working memory tasks, i.e. the serial recall and operation span tasks. Performance deteriorated in the sound condition with the highest intelligibility (*STI* 0.65) compared with the other two conditions. There was no difference between the lowest *STI* values (0.10 and 0.35), suggesting that the drop in performance occurred between *STI* 0.35 and *STI* 0.65. There was a similar, although only marginally significant effect ($p = .05$) in the knowledge access component of the reading comprehension task. Other than that, the complex and semantic tasks (reading comprehension and proofreading) were not affected by the *STI* of background speech. Visuo-spatial serial memory was not affected by the sound condition either.

Unlike task performance, subjective disturbance differed between all sound conditions, increasing with increasing speech intelligibility. The perceived disturbance by background speech also increased with growing *STI*. The average disturbance by the background sound (i.e., the masking sound) was low and did not differ between conditions even though the sound level varied from 38 to 48 dBA. Thus, the acoustic disturbance resulted from speech intelligibility, not the masking sound level.

Taken together, the results support the assumptions that background speech impairs both cognitive performance and subjective perceptions of the acoustic environment, and that these effects can be explained by the *STI* of speech. The results are compatible with Hongisto's (2005) model which suggests a non-linear relation between the *STI* and performance. However, the model may not be generalisable to more complex tasks which include semantic processing demands. The use of masking sound as a means of improving the acoustic conditions is supported by the findings.

4.2 STUDY II

Haapakangas, A., Kankkunen, E., Hongisto, V., Virjonen, P., Oliva, D., & Keskinen, E. (2011). Effects of five speech masking sounds on performance and acoustic satisfaction - implications for open-plan offices. *Acta Acustica united with Acustica*, *97*(4), 641-655.

The purpose of this study was to compare different masking sounds in terms of their effects on cognitive performance and acoustic satisfaction. Five masking sounds were investigated: filtered pink noise, ventilation noise, instrumental music, vocal music (i.e., music containing lyrics) and the sound of spring water. The masking sound was superimposed to background speech. The *STI* values of the masked speech conditions were 0.35-0.40. The masked speech conditions were compared with silence (*STI* 0.00) and unmasked speech (*STI* 0.62), making the total number of conditions seven. Sound condition was manipulated within participants. In each condition, the participants performed a serial recall task, a proofreading task and a creative thinking task. A questionnaire on the perception of the acoustic environment was filled in at the end of each sound condition. Composite variables were formed for acoustic satisfaction (12 items) and subjective workload (4 items). The disturbance caused by speech and masking sound was rated separately, as in Study I.

Three research questions were investigated. First, it was examined whether unmasked speech (*STI* 0.62) and masked speech (*STI* 0.35-0.40) impaired cognitive performance and acoustic satisfaction in comparison to silence. Second, it was examined whether the masked conditions improved performance and acoustic satisfaction in relation to unmasked speech. Third, the five masked speech conditions were compared with each other to determine whether the masking sound type had an effect on performance or acoustic satisfaction independent of the *STI*.

The results showed a main effect of sound condition on performance in the serial recall task. Compared with silence, the error rates increased in the unmasked speech and the three masked speech conditions, including vocal music, ventilation noise and filtered pink noise. Of the masked speech conditions, only the spring water condition decreased error rates in comparison to unmasked speech. Paired comparisons between masked speech conditions showed that spring water sound improved performance in comparison to vocal music and ventilation noise. There was also a marginal effect of sound condition on creative thinking (p = .075), suggesting higher ideational originality in the spring water condition in comparison to all other conditions. Taken together, the performance measures indicated that, among the masked speech conditions, the best results were obtained with the spring water sound and the poorest results with vocal music and ventilation noise.

The subjective ratings differentiated to a greater extent between the conditions than the performance measures. Acoustic satisfaction was highest in silence, differing from unmasked speech and all masked speech conditions. Compared with unmasked speech, acoustic satisfaction was improved in all masked speech conditions, indicating benefits from masking and a lower *STI*. Among the masked speech conditions, the highest ratings of acoustic satisfaction were obtained with spring water sound and filtered pink noise whereas the lowest satisfaction was experienced in the vocal music condition. Significant differences were observed between spring water sound and vocal music, and between filtered pink noise and both music conditions (vocal and instrumental). The pattern of results was similar for subjective workload, except that the ratings were equally high in unmasked speech and the vocal music condition. The separate ratings of the disturbance caused by each masking sound showed that particularly vocal, but also instrumental, music was perceived as more disturbing than the three continuous sounds (filtered pink noise, ventilation noise and spring water). The average disturbance caused by the latter three was low.

To conclude, the results support the use of masking sound in decreasing distraction caused by background speech. The use of masking sound is beneficial particularly for the subjective perceptions of the acoustic conditions, but also for some cognitive tasks. Furthermore, the masking sound type is important in addition to the achieved *STI*. Together, the evidence from cognitive and subjective measures supports the use of spring water sound and filtered pink noise, whereas the use of music as a general masking sound is not recommended, particularly if it contains lyrics. The results contradict Hongisto's (2005) model to some extent because the effects of different masking sounds cannot be explained by the *STI* alone.

4.3 STUDY III

Haapakangas, A., Hongisto, V., Hyönä, J., Kokko, J., & Keränen, J. (2014). Effects of irrelevant speech on performance and subjective distraction: The role of acoustic design in open-plan offices. *Applied Acoustics*, *86*, 1-16.

The aim of this study was to investigate the relation between the *STI* and cognitive and subjective effects of background speech in a more ecologically valid way. Instead of playing artificially modified audio material, the sound conditions were created by building three different room acoustic conditions using absorption materials, screens and a masking sound system. The *STI* also varied within conditions due to a bigger laboratory (82 m^2, 12 workstations) where the distance to the speech sources varied.

The experiment included four conditions: three conditions with background speech (*noAbs_noMask, Abs_noMask,* and *Abs_Mask)* and a quiet control condition. The room acoustic measurements showed that the changes in the room acoustic design had a larger effect on the *STI* 6 meters away which ranged from 0.11 (*Abs_Mask*) to 0.60 (*noAbs_noMask*). However, the *STI* remained above 0.50 at the nearest workstation (2-meter distance) in all conditions that contained speech. The room acoustic conditions were somewhat similar between *noAbs_noMask* and *noAbs_Mask* (**Table 3**).

The acoustic condition was manipulated between groups. Tasks were performed in three consecutive blocks. The serial recall, N-back, and operation span tasks were done in each block but the text memory task was only performed once. Each task was followed by a NASA-TLX rating. A questionnaire on the subjective perceptions of the acoustic conditions was completed at the end of the experiment.

The results showed that the serial recall and working memory tasks were affected by the acoustic condition whereas the text memory task was not. However, the effect of acoustic condition tended to mainly involve the difference between the quiet condition and either of the conditions with the highest speech intelligibility (*noAbs_noMask* and *noAbs_Mask*). Benefits of the room acoustic design on performance were only observed in the N-back task where reaction times decreased in *Abs_Mask* compared with *noAbs_noMask*. There were no interactions between the acoustic condition and exposure time in any of the tasks, suggesting that the effects of acoustic condition were neither attenuated nor amplified within the three-hour working period.

As in Studies I and II, the subjective ratings provided more consistent and stronger evidence for the assumed effects of room acoustic design. Perceived disturbance decreased in the optimal acoustic design (*Abs_Mask*) as opposed to the conditions with higher *STI* values, while the lowest disturbance was observed in the quiet condition. The subjective ratings were compatible with the room acoustic measurement data, showing that the acoustic condition affected the perceived distraction by speech from workstations further away but not from the nearest workstation. The effects of acoustic condition on subjective distraction were stronger among noise-sensitive participants, suggesting that they benefited more from acoustic improvements than non-sensitive participants.

To conclude, the results suggest that the negative effects of background speech can be decreased by room acoustic design in realistic conditions where the direction of speech and the distance to speech sources vary. Reducing speech intelligibility by room acoustic means seems beneficial particularly for subjective perceptions of the acoustic conditions. The effects of room acoustic measures on cognitive performance may be limited by the relatively high speech intelligibility between adjacent workstations. The results support the use of masking sound by showing that the use of maximum attenuation without masking sound is not effective in decreasing cognitive nor subjective problems related to background speech.

4.4 STUDY IV

Haapakangas, A., Hongisto, V., Eerola, M., & Kuusisto, T. (2017). Distraction distance and perceived disturbance by noise - An analysis of 21 open-plan offices. *Journal of the Acoustical Society of America, 141(1), 127-136.*

The aim of this study was to synthesise evidence from 21 open-plan offices to examine whether the distraction distance (r_D) predicts perceived noise in open-plan offices. The relation between the other parameters of ISO 3382-3 (the spatial decay rate of speech, $D_{2,S}$, the *SPL* of speech at a 4-meter distance, $L_{p,A,S,4m}$, and the *SPL* of background noise, $L_{p,A,B}$) and perceived noise disturbance was also examined.

The descriptive statistics showed that, on average, 37% of employees reported high disturbance by noise. The variation between offices was large, ranging from 6.4% to 70.8%. Noise disturbance was lower among activity-based offices (6.4-30 %), compared with traditional open-plan offices (16.7-70.8%). There was a strong correlation (r=0.88) between the outcome variables (disturbance by noise in general and disturbance by background speech), suggesting that distracting background speech largely explained the overall perception of disturbing noise.

The results of the statistical models, adjusted for age and gender, showed that an increase in r_D was associated with increased odds of high disturbance in both samples and for both outcome variables (OR 1.09-1.14). These effect sizes per one meter increase in r_D are small. However, a 1-meter difference is not practically meaningful and likely falls within the measurement error of r_D. The obtained OR's correspond to an approximately 54-93% increase in the odds of high disturbance for a 5-meter increase in r_D.

An increase in $L_{p,A,S,4m}$ was associated with increased odds of high disturbance whereas an increase in $L_{p,A,B}$ was associated with decreased odds. However, these findings were not observed in the sample excluding activity-based offices and they are, thus, less reliable. Particularly the results related to $L_{p,A,S,4m}$ may have been biased by the inclusion of activity-based offices in the complete sample because these offices had both low $L_{p,A,S,4m}$ and low noise disturbance. $D_{2,S}$ was not associated with the outcome variables in any of the models.

To conclude, the results suggest that r_D predicts perceived noise disturbance in open-plan offices, supporting its use as an indicator of the room acoustic quality. The results also support the use of masking sound by demonstrating that an increase in the background noise level is associated with decreased noise disturbance.

4.5 STUDY V

Haapakangas, A., Hongisto, V., Varjo, J., & Lahtinen, M. (2016). Benefits of alternative workspaces in open-plan offices with fixed workstations – evidence from two office relocations. (Manuscript submitted for publication)

The aim of this study was to examine office distractions as a potential mediator of other negative outcomes in open-plan offices, and to investigate the benefits of additional quiet workspaces for environmental perceptions and employee stress. Data from two longitudinal studies were combined. Two organizations moved from private offices to modern open-plan offices that differed in the number and variety of quiet workspaces. The number of quiet workspaces was much higher in Organization A compared with Organization B. Personal workstations were retained in both offices.

Survey data were gathered once before (Time 1) and once after (Time 2) the office change. The main outcomes were distractions, environmental satisfaction, collaboration and stress symptoms. Distractions and collaboration were also considered as mediators in some of the analyses. The composite variable for distractions correlated strongly with the perception of noise in general (r=0.87-0.90) and with distraction from background speech (r=0.73-0.79). Room acoustic measurements (ISO 3382-3) were conducted in both open-plan offices. The room acoustic quality of the offices was similar: the distraction distance (r_D) was 14 meters in Organization A and 12 meters in Organization B, indicating fairly poor room acoustic conditions in both.

Quasi-experimental analyses showed that, at Time 1, the organizations did not differ from each other in perceived distractions, collaboration or stress symptoms.

Environmental satisfaction was higher in Organization B. At Time 2, all outcomes were significantly worse in Organization B where the number and variety of quiet workspaces was lower. Within-participants analyses showed that, following the office relocation, distractions and stress symptoms increased in Organization B while environmental satisfaction and collaboration deteriorated. Distractions also increased in Organization A but less than in Organization B. On average, environmental satisfaction and collaboration appeared unchanged in Organization A. However, a closer examination revealed two opposing patterns: nearly half of the respondents experienced a decline in these outcomes while one third experienced an improvement. Stress symptoms decreased after the office change in Organization A.

Simple mediation models showed that increased distractions mediated the negative changes in environmental satisfaction, collaboration and stress symptoms in Organization B. However, distractions did not alone explain the negative change in environmental satisfaction as the direct effect also remained significant (path *c'* in **Figure 5**). Increased distractions also mediated negative changes in environmental satisfaction and collaboration in Organization A. A serial model which included both distractions and collaboration as mediators showed that the increase in stress symptoms in Organization B was mediated by a serial path from increased distractions to impaired collaboration (path $a_1a_3b_2$ in **Figure 5**), but not by either mediator alone. This mechanism was not observed in Organization A.

The perception of the alternative quiet workspaces was associated with the key outcome variables in both organizations at Time 2. That is, satisfaction with the quiet workspaces correlated positively with environmental satisfaction and collaboration, and negatively with distractions and stress symptoms. Three groups ('low need', 'matched need' and 'mismatched need') were formed on the basis of two questions: the need for quiet workspaces and the perceived ease of access to such spaces. The 'low need' group included the respondents who did not regularly need quiet workspaces (41% in Organization A, 46% in Organization B). The match between employee needs and the availability of private workspaces was strongly related to the office design, as 49% of the respondents in Organization A but only 9% in Organization B belonged to the 'matched need' group (i.e., those who needed quiet workspaces regularly and were able to access them easily when needed). The 'mismatched need' group included those who could not access quiet workspaces easily despite a regular need (10% in Organization A, 45% in Organization B). This group was less satisfied with the environment, experienced more distractions and stress symptoms, and perceived collaboration more negatively than the other groups. The 'low need' group and 'matched need' group did not differ from each other in the key outcomes. The 'mismatched need' group was characterised by higher cognitive work demands than the 'low need' group. The need for interaction, multi-locationality, working time at one's workstation and age did not differentiate the groups in either organization.

Overall, the work was more multi-locational in Organization A at Time 2. This may have contributed to its more positive results in addition to the differences in office design. However, most of the work was done at the personal workstation in both organizations at Time 2.

Taken together, the findings support the assumption of office distractions as a mediating factor for other negative changes observed after moving to an open-plan office. Yet, perceived distractions and related negative outcomes can be decreased by providing alternative quiet workspaces that are easily accessible. The results highlight office design as a complementary way for decreasing acoustic distraction in open-plan offices.

5. DISCUSSION

In this thesis, I have investigated the effects of office noise on cognitive performance and subjective reactions in open-plan offices. Specifically, I have focused on the effects of background speech, and on speech intelligibility as a predictor of these effects. Combining evidence from laboratory experiments and field studies, this thesis provides new information on both problems and possible solutions related to the disturbance caused by background speech and other office distractions.

The results show that office noise is a multifaceted problem in contemporary open-plan offices. In a sample of 21 open-plan offices, 37% of employees reported high disturbance by office noise (Study IV). The variation between offices was large, with over 70% of employees experiencing high noise disturbance in the worst case. Although conclusions cannot be drawn on the general prevalence of noise complaints due to the sample characteristics, the results show that the general perception of both disturbing noise (Study IV) and disturbing office distractions (Study V) is strongly correlated with distracting background speech. These observations are compatible with the literature describing background speech as a central noise problem in open-plan offices (e.g., Banbury & Berry, 2005; Pierrette et al., 2015; Schlittmeier & Liebl, 2015) and support the operationalization of office noise as background speech in the laboratory experiments of this thesis. The laboratory studies (I, II and III) show that intelligible background speech increases particularly subjective perceptions of acoustic disturbance but also impairs cognitive performance. Study V shows that increased office distractions, including noise, mediate the negative changes in environmental satisfaction, collaboration and stress symptoms that emerge after moving to an open-plan office. Even though offices applying activity-based working appear to have lower noise disturbance than more traditional open-plan offices (Study IV), they may also entail some of the risks related to increased distractions (Study V), at least in offices where personal workstations are retained.

In the following, I will discuss the results in relation to the two general themes of this thesis, beginning with the problems and moving then to the solutions and practical implications. The discussion follows the order of the stated research questions (see Section 2), moving from more theoretical laboratory findings to observations in field studies within both themes.

5.1 Problems related to office noise

5.1.1 *STI* as a predictor of the cognitive effects of background speech

Overall, the experimental evidence from Studies I to III support the *STI* as a predictor of the detrimental effects of background speech in short-term memory and working memory tasks. The observed relation between speech intelligibility and performance is in line with previous studies (Colle, 1980; Ellermeier & Hellbrück, 1998; Schlittmeier et al., 2008; Venetjoki et al., 2006) as well as more recent research (Brocolini et al., 2016; Ebissou et al., 2015; Hongisto, Varjo et al., 2016; Jahncke et al., 2013; Keus van de Poll et al., 2014; Keus van de Poll et al., 2015; Liebl et al., 2016; Schlittmeier & Hellbrück, 2009). This thesis has contributed to the literature by demonstrating that background speech not only impairs serial recall but also working memory tasks. The latter types of tasks, particularly complex span tasks, have been associated with higher-order cognitive abilities, such as fluid intelligence (Kane et al., 2007; Unsworth et al., 2009). Thus, the results from working memory tasks seem more meaningful for real-life work performance than the earlier findings on serial recall. However, short-term memory and working memory appear to be largely overlapping constructs (e.g., Aben, Stapert, & Blokland, 2012; Colom, Shih, Flores-Mendoza, & Quiroga, 2006). It is, therefore, uncertain whether any specific working memory processes contributed to the present results in addition to the serial processing and short-term storage requirements that were included in both the serial recall and working memory tasks. Visuo-spatial serial memory was not affected by background speech (Study I). Thus, the present evidence suggests that the disruption caused by background speech concerns particularly verbal serial recall and working memory tasks. The effects of background speech on visuo-spatial tasks cannot be excluded based on these results, particularly as such effects have been previously reported (Jones et al., 1995).

The model of Hongisto (2005) receives some support from Studies I and II. This thesis did not specifically test the model as its most critical value, *STI* 0.50, was not included. However, the observed decrements in performance occurred between *STI* 0.35 and 0.65 which roughly includes the range (*STI* 0.30-0.50) where the steepest decline is supposed to take place according to Hongisto (2005). As differences between *STI* 0.10 and 0.35 were not found, the findings are also compatible with the general non-linear shape of the *STI*-performance curve (Hongisto, 2005, **Figure 1**). However, the results of Study II partly contradict the model by showing that the *STI* alone is not a sufficient descriptor of performance effects. Based on the *STI*-model (Hongisto, 2005), no differences should have been found between five masked conditions with similar *STI* values. Yet, spring water sound outperformed the other masking sounds, particularly vocal music and ventilation noise, in its effects on serial recall. In fact, spring water sound completely abolished the *ISE,* as performance was not reduced in comparison to the silent control condition. This finding has since been replicated by Keus van de Poll et al. (2015).

The method of determining the *STI* may explain some of the inconsistencies in the observed *STI*-performance relations in Study II. The calculation method takes into account the changes in the *SPL* of speech but not any variation in the masking sound. Thus, the *STI* is most accurate for constant sounds that are typically used in masking. However, the spring water sound contained rapid level modulations which may coincide with the fastest level modulations of speech. It is possible that a more advanced method, which considered the modulations of background noise with respect to speech, would have resulted in a lower *STI* value for the spring water sound. Such result would be more compatible with the *STI*-performance model (Hongisto, 2005). Taken together, Hongisto's (2005) model seems most valid when the reduction of *STI* is achieved with a masking sound that is quite constant in time, such as filtered pink noise.

Since the publication of Studies I and II, several other researchers have also reported data on the relation of the *STI* and serial recall performance (Ebissou et al., 2015; Hongisto, Varjo et al., 2016; Keus van de Poll et al., 2015; Liebl et al., 2016). These findings are presented together with the results from Studies I and II in **Figure 6**. In order to evaluate Hongisto's (2005) model, all of the existing evidence needs to be considered together because the conclusions of any single study are restricted by the chosen *STI* values, the number of comparison points and their distance from each other. Studies I and II included three *STI* conditions which limits the observation of the exact shape of the *STI*-performance curve. The results of Keus van de Poll et al. (2015) and Liebl et al. (2016) demonstrate that the difference between successive *STI* conditions (e.g., 0.38 and 0.46) may not be statistically significant even though it is apparent that the performance effect increases between them when the evidence from all paired comparisons of the experiment is considered. Thus, the failure to obtain a significant difference between *STI* 0.10 and 0.35 (Study I), where the deterioration of performance is assumed to begin (Hongisto, 2005), may have simply resulted from a too small effect size. This is supported by recent evidence (Hongisto, Varjo et al., 2016) showing that only a slight increase between these points of comparison (*STI* 0.08 vs. *STI* 0.38) produces an effect on serial recall performance. As **Figure 6** shows, the combined evidence from recent studies suggests that the performance effect likely begins below STI 0.35.

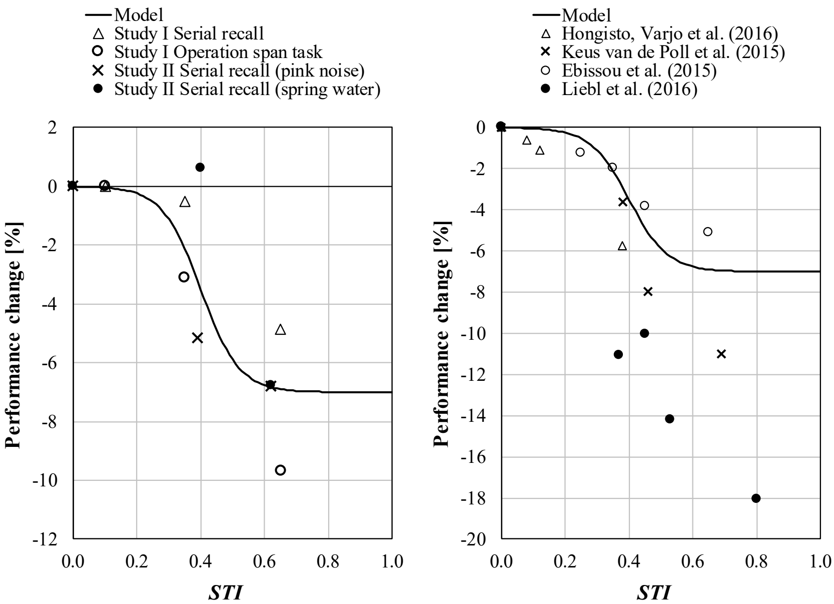

Figure 6. The results of Studies I and II (left) and more recent findings on serial recall performance (right) in relation to the prediction model by Hongisto (2005). Performance change is defined as the difference between the percentage of errors in silence (STI 0.00) and in speech, as done by Hongisto (2005). The results of Study II are presented in relation to STI 0.10 because the study did not include STI 0.00. The data points are based on STI conditions with constant background sounds (e.g., filtered pink noise), except for STI 0.38 by Keus van de Poll et al. (2015) and Study II which used water sounds.

The finding that performance deteriorated between *STI* 0.35 and *STI* 0.65 is compatible with several recent studies (Ebissou et al., 2015; Keus van de Poll et al., 2015; Liebl et al., 2016) which are shown in **Figure 6**. Liebl et al. (2016) found that performance decreased from *STI* 0.00 to *STI* 0.37 and 0.45, from *STI* 0.45 to 0.53 and from *STI* 0.53 to 0.80. Keus van de Poll et al. (2015) showed that performance did not change between silence (STI 0.00) and STI 0.38, but decreased between STI 0.38 and 0.69. However, STI 0.38 was achieved using a water sound and may not be comparable to the other STI conditions in which constant sounds were used. Keus van de Poll et al. (2015) also included a pink noise condition with STI 0.46 (**Figure 6**) but did not report whether it differed from STI 0.69. The results from Ebissou et al. (2015) suggest that performance is impaired somewhere between *STI* 0.25 and 0.65 but this study lacks statistical comparisons between conditions. Originally, Hongisto (2005) assumed that performance is impaired between 0.20 and 0.60 with the steepest drop occurring between 0.30 and 0.50. Taken together, the existing evidence suggests that performance starts to decrease below *STI* 0.35 but may continue to deteriorate up to slightly higher STI values than Hongisto's (2005) model predicts. The range where performance deteriorates may also be wider than Hongisto (2005) assumed although the number of studies is still rather limited for making precise claims. Importantly, the existing evidence does not contradict the suggestion that *STI* 0.50 can be considered as a critical target level below which the deteriorating effect is substantially decreased.

However, these conclusions may only apply to verbal short-term memory and working memory tasks. Although some of the other working memory processes may also contribute to the disruption, these results suggest that Hongisto's (2005) model mainly applies to process-based interference that is related to serial memory. In this thesis, no effects were observed in more complex and semantic tasks although a non-significant trend appeared in the creative thinking task (Study II) and in one component of the reading comprehension task (Study I). These results are somewhat surprising given that the existence of semantic interference has been documented in several tasks, including some of the task types used in this thesis (proofreading, Jones et al., 1990; reading comprehension, Oswald et al., 2000). On the other hand, previous studies on speech intelligibility have not observed an effect on reading comprehension either (Liebl et al., 2012; Venetjoki et al., 2006). One explanation for the conflicting results might be related to any differences in top-down control between tasks. For example, the negative effect of background speech on memory for written prose can be attenuated by increased task engagement (Halin et al., 2014) and the disturbance of reading comprehension can be compensated by changes in the reading process (Hyönä & Ekholm, 2016). The *ISE*, in turn, is known to be immune to cognitive control (Hughes, 2014). Some support for compensatory efforts can be found from Study I in which the self-rated task difficulty of the proofreading task increased with increasing *STI* in the absence of decrements in task performance. It is also important to remember that the background speech was not continuous but alternated between speech and silence, unlike in most other speech intelligibility studies. It is possible that the short silent pauses increased the possibility to compensate for noise effects in the more complex tasks because they were more self-paced than the short-term memory and working memory tasks.

Another possibility is that the critical *STI* value is lower in tasks in which the disruption is based on semantic interference, rather than the changing state effect. Keus van de Poll et al. (2014) have shown that the maximum deterioration in story-writing, which is another complex task involving semantics, is already reached at *STI* 0.23, whereas the impairment of a semantic short-term memory task increases until *STI* 0.34 (Jahncke et al., 2013). This might also explain the lack of significant effects in Study I. If the maximum performance occurred around, for example, *STI* 0.20, the lowest *STI* (0.10) might have been too close for the difference between 0.10 and 0.35 to reach statistical significance. However, this explanation is contrasted by the observation that the complex and semantic tasks were not impaired in comparison to silence (Studies II and III). Thus, methodological issues related to the reliability and sensitivity of the tasks are also potential explanations, as it is very difficult to design different task versions with identical processing demands for more complex tasks. In addition, the complexity of the experimental designs (Studies II and III) may have resulted in some loss of statistical power, increasing the risk of Type II error.

5.1.2 Subjective effects of background speech varying in intelligibility

As in other studies (Keus van de Poll et al., 2015; Schlittmeier et al., 2008; Schlittmeier & Hellbrück, 2009; Venetjoki et al., 2006), the subjective measures were more sensitive to differences between acoustic conditions and provided more consistent evidence for the effects of the *STI* in all experiments. Whereas the *STI*-performance relation seems to be non-linear and change rapidly within certain range (e.g., Hongisto, 2005; Jahncke et al., 2013), the subjective disturbance increases more linearly with increasing *STI*. The increase in subjective disturbance also emerges at lower *STI* values than the performance effects. The subjective measures show that a silent work environment is clearly preferred by the participants (Studies II and III) even when there are no objective differences in performance.

The difference between cognitive performance and subjective disturbance is compatible with the enhanced effort hypothesis (Schlittmeier et al., 2008) and the resource-based framework of performance under stress (Hancock & Warm, 1989; Hockey, 1997; Szalma & Hancock, 2011) within which the compensatory efforts would be interpreted as latent decrements of performance. Combined with the data from the performance tests, the results suggest that most of the tasks in Studies I and III were affected subjectively and/or objectively. In Study III, the evidence on subjective performance effects is, however, very limited because most of the subscales of NASA-TLX were not affected by the acoustic conditions. Study II did not include task-specific workload ratings.

The pattern of subjective disturbance does not follow Hongisto's (2005) model but shows that, in a context where individuals concentrate on task performance, they are subjectively affected at much lower levels of speech intelligibility than *STI* 0.50. If one accepts the argument that subjective disturbance reflects latent decrements of performance, the criteria for the distraction distance (r_D) should be much lower than *STI* 0.50 which is largely supported by performance effects in specific tasks with serial processing demands.

5.1.3 Office distractions as a mediator of the negative outcomes of an environmental change

Study V investigated office distractions as a potential mediator for other negative outcomes observed in open-plan offices. The results showed that when workers moved from private offices to a modern open-plan office, the negative changes observed in environmental satisfaction, perceived collaboration and stress symptoms were largely mediated by increased distractions. Only a few studies have previously examined distraction-related variables as possible mediators in open-plan offices and these studies have been restricted to correlational study designs (Herbig et al., 2016; Laurence et al., 2013). The mediating role of distractions is further supported by the finding that this mechanism emerged in two organizations that differed in the physical office design and overall outcomes of the office change. Although the composite variable was not restricted to auditory distractions, it correlated highly with perceived noise and disturbing background speech. Thus, the conclusions concerning the role of distractions can be generalised to office noise with some caution. The results are in line with evidence viewing the acoustic conditions and lack of privacy as a central problem in open-plan offices (Bodin Danielsson & Bodin, 2009; De Croon et al., 2005; Pejtersen et al., 2006; Sundstrom et al., 1982). Furthermore, the results demonstrate that the risks observed in earlier studies are shared, at least to some extent, by modern open-plan office designs that include alternative workspaces.

In addition, the negative effects of office distractions on stress symptoms were mediated through impaired collaboration. This mechanism has not been explored by any previous study. The development of stress symptoms following an environmental change is likely a complex process where the magnitude of distraction and the possibilities of coping also play a role (cf. Szalma & Hancock, 2011). This may explain why increased distractions and impaired collaboration did not increase stress symptoms in the organization where the level of perceived distraction was much lower and where plenty of additional workspaces were provided. It should be noted that the exact mechanism for the association between distractions and impaired collaboration remains unidentified. Possible explanations include impaired interpersonal relations (Bodin Danielsson et al., 2015) and decreased interaction, either due to a concern of disturbing others (Parkin, Austin, Pinder, Baguley, & Allenby, 2011) or due to increased remote working to escape office distractions (Haapakangas et al., 2008). It may also be that impaired collaboration is not a source of stress but rather reflects diminished social support which is an important moderator in the perception and the effects of stress in general (Viswesvaran, Sanchez, & Fisher, 1999). The links between office distractions, interpersonal relations and stress are an important topic for future research.

Overall, these results indicate that office distractions are not only risks for environmental dissatisfaction but may have more extensive negative implications for the organization. In the following, I turn to the findings concerning possible ways of reducing perceived noise and related problems in open-plan offices.

5.2 Solutions to noise problems in open-plan offices

5.2.1 Use of masking sound

The use of masking sound in decreasing acoustic dissatisfaction is clearly supported by the experimental findings (Studies I, II and III) and the field study involving 21 offices (Study IV). In the laboratory studies, the perception of the acoustic conditions was explained by the presence and intelligibility of background speech, not the masking sound level. Constant masking sounds were not perceived as disturbing and their disturbance did not increase when their level was increased. In Study IV, higher background noise level was associated with lower noise disturbance in open-plan offices. These results suggest that masking sound is not a source of noise in open-plan offices but is perceived positively, due to its association with lower speech intelligibility. Thus, constant masking sounds can be recommended for general use in open-plan offices. However, even though levels as high as 48 dB did not cause disturbance in Study II, other studies recommend 45 dB as the maximum masking sound level (Bradley, 2003; Veitch et al., 2002). Higher levels are suspected to increase the risk of annoyance and stress reactions.

In addition to filtered pink noise, spring water sound proved to be both an efficient and pleasant masking sound. These results were surprising but have since been supported by Keus van de Poll et al. (2015). As noted above (see Section 5.1.1.), the superiority of the spring water sound may have resulted from its acoustic properties. Another possibility is suggested by the literature on the positive psychological, physiological (Ulrich et al., 1991) and cognitive (Berman, Jonides, & Kaplan, 2008) effects of exposure to nature. Although the studies on restorative effects have mostly included visual or in-vivo exposure, a few studies have shown that water sounds without visual stimuli may also positively affect stress-related measures (Jahncke et al., 2011; Thoma et al., 2013). However, it is uncertain whether water sounds would elicit positive associations in office environments where they do not naturally belong. Haga, Halin, Homgren, and Sörqvist (2016) have shown that the restorative effects of ambiguous water-like sound do not depend on the stimulus-features per se but on whether the sound is interpreted as a natural sound. Taken together, field studies are needed to confirm the applicability and acceptability of water sounds in open-plan offices before they can be recommended for wider commercial use.

Music is another sound that has been associated with positive effects on stress response (Thoma et al., 2013). However, it cannot be recommended as a general masking sound in offices. Particularly music containing lyrics is a poor masking sound in terms of both performance and subjective measures (Study II). This is logical, given that singing adds another source of 'speech' and two simultaneous voices do not mask each other efficiently (Jones & Macken, 1995). Accordingly, vocal music is more detrimental to cognitive performance than instrumental music when tested independently without simultaneous speech (Martin et al., 1988; Salamé & Baddeley, 1989). The results regarding the use of instrumental music as a masking sound were mixed (Study II). Particularly the subjective, but also the cognitive effects of music may depend on individual differences, including certain personality traits (Furnham & Bradley, 1997). For individuals who do not perceive it as a distraction, listening to instrumental music with headphones may be an appropriate noise abatement measure in open-plan offices.

5.2.2 Room acoustic design and distraction distance

Bridging the gap between the use of the *STI* in laboratory experiments and the use of its room acoustic equivalent, r_D, in real offices is one of the key points of this thesis. Studies III and IV provide a unique investigation of this issue. Based on Study III, the benefits of decreasing the *STI* may be weaker in real office environments than other laboratory findings, including Studies I and II, suggest (e.g., Jahncke et al., 2013; Keus van de Poll et al., 2014). Compared with the room acoustic data of the real offices in Study IV, the best condition of Study III (*Abs_Mask*, r_D = 3.4 m) was close to exceptionally good offices whereas the condition with no room acoustic treatment (*noAbs_noMask*) had an unrealistically high r_D (38 m). Given that Study III exaggerated differences in room acoustic quality, it is surprising that the serial recall and operation span tasks, which were affected by the *STI* in Study I, only tended to be impaired in comparison to the quiet control condition. The benefits of room acoustic design were, however, observed in the N-back task and in the subjective perceptions of the acoustic conditions. The differences between conditions were stronger among noise-sensitive individuals, possibly suggesting that they benefited more from the room acoustic improvements.

There are a few possible explanations for the modest results in the objective performance measures of Study III. First, the results may reflect a more accurate effect of reduced speech intelligibility in terms of ecological validity because Study III was designed from a practically motivated, rather than a theoretical point of view. Specifically, the experimental design included the physical limitations that are associated with reducing the *STI* at short distances between a speaker and a listener. The fact that the effect of room acoustic elements becomes more pronounced with increasing distance (Keränen et al., 2012; Virjonen et al., 2009) is also apparent in the subjective responses which showed that the acoustic condition had an effect on the perceived distraction of speech from remote workstations but not from the adjacent workstation. Study III demonstrates that open-plan offices with an optimal acoustic design are not accurately characterised by a low *STI* but rather with less frequent exposure to background speech exceeding *STI* 0.50. Therefore, the effect of acoustic improvements on performance will, in practice, be smaller than has been suggested by previous studies where the limitations related to room acoustic design have not been considered.

Methodological limitations are another explanation for the limited cognitive effects in Study III. Particularly the between-participants manipulation of acoustic conditions may have weakened the possibility of observing differences between conditions even though some individual differences were taken into account in the analyses. This explanation is supported by a related study (Varjo et al., 2015) which involved a within-subject manipulation of two conditions in the same laboratory. The acoustic properties of the conditions were similar to the acoustically best and worst condition of Study III but they were combined with changes in temperature and ventilation rate. In this study, the serial recall, operation span and N-back tasks were all affected. Even though interactions between indoor environmental factors cannot be ruled out, the room acoustic differences likely contribute to the observed results because the tasks were mostly unaffected by independent manipulations of temperature (Maula, Hongisto, Östman, et al., 2016) and ventilation rate (Maula, Hongisto, Naatula, et al., 2016). Thus, the effects of room acoustic design were likely underestimated in Study III due to the between-participants manipulation of the acoustic condition.

Given the uncertainties related to the results of Study III, Study IV provides valuable evidence on the role of room acoustic design, showing that an increase in r_D is associated with increased odds of high noise disturbance in real open-plan offices. To date, the assumptions on the role of r_D have been based on laboratory experiments (e.g., Jahncke et al., 2013; Keus van de Poll et al., 2014; Venetjoki et al., 2006; Studies I, II and III) and case studies at single workplaces (Hongisto, 2008; Hongisto et al., 2012; Hongisto, Haapakangas et al., 2016). The extent to which these findings can be generalised has been uncertain, particularly as the previous cross-sectional study by Newsham et al. (2008) did not find evidence of a relation between acoustic satisfaction and speech intelligibility. The results of Study IV are in line with the laboratory and field studies concerning the *STI* and extend this area of research to more general and realistic conditions. The differences between the present results and those of Newsham et al. (2008) are likely explained by the ISO 3382-3 measurement method which considers the acoustic quality of the whole office space. Newsham et al. (2008) measured the acoustic conditions between neighbouring workstations only.

This thesis has important practical implications for the room acoustic design of open-plan offices. The use of r_D as an indicator of the room acoustic quality of open-plan offices is supported by the results. Even though room acoustic design cannot eliminate potential distraction from adjacent workstations (Study III; Keränen et al., 2012), its impact on the intelligibility of more remote voices nevertheless seems sufficient and relevant to the perception of noise disturbance. Based on the present results, acoustic conditions should not be evaluated using only parameters that are mainly related to the attenuation of noise levels (e.g., $L_{p,A,S,4m}$ and $D_{2,S}$ in ISO 3382-3). r_D and the other ISO 3382-3 parameters could also be applied in the National Building Code which currently does not give any obligatory requirements for open-plan offices in Finland. Voluntary guidelines using r_D and other ISO parameters have already been published (e.g., SFS 5907 standard in Finland). It is important to note that the possibility that the critical *STI* value is smaller than 0.50 for certain types of tasks (see Section 5.1.1.) does not contradict the observed relation between r_D and noise disturbance, nor the use of ISO 3382-3 in room acoustic measurements. This information could be simply taken into account in the interpretation of r_D by using smaller values as a criterion for a certain acoustic class.

The acoustic conditions of an open-plan office can be improved by decreasing $r_{D.}$ Room acoustic studies show that this requires the simultaneous use of screens, absorption in room and furniture surfaces, and masking sound (Bradley, 2003; Keränen et al., 2012; Keränen & Hongisto, 2013). Keränen and Hongisto (2013) have also published a model which includes an online prediction tool for estimating the effects of different room acoustic measures on the acoustic conditions in a specific office space. Based on Studies III and IV, very small changes in r_D are likely ineffective in decreasing perceived noise disturbance. Instead, the decrease in r_D should be obvious.

5.2.3 Alternative quiet workspaces

As speech intelligibility cannot be decreased efficiently between adjacent workstations, workers continue to need quiet workspaces for concentration. Such workspaces are provided in many contemporary offices. The benefits of quiet workspaces are highlighted by both the quasi-experimental and the correlational analysis of data in Study V. The number of quiet workspaces and the ease of access (e.g., proximity) seem particularly important in preventing or mitigating the risks related to office distractions. It should be noted that the organization with superior results provided an exceptionally high number of quiet workstations (one per 2.5 employees). Including a sufficient number of spaces for quiet work may be at odds with the goal of high space-efficiency because a significant amount of space is required for alternative workspaces, at least if personal workstations are retained.

The present findings are consistent with the results of Hoendervanger et al. (2016) who showed that the frequency of workspace switching is not associated with environmental satisfaction as such. In the light of the present results, it is rather the match between the need for more private spaces and the ease of access to such workspaces that is associated with environmental perceptions and other outcomes. The mismatch between employee needs and the availability of quiet workspaces was strongly related to the office design but also to the concentration demands of the job. The subgroup with mismatched needs was characterised by higher concentration requirements than the group who did not perceive a regular need for quiet spaces. These results are in line with findings that the effects of low privacy and office distractions on employee reactions are modified by concentration requirements (Seddigh, Berntson, Bodin Danielson, & Westerlund, 2014) and task complexity (Block & Stokes, 1989; Maher & von Hippel, 2005).

Re-designing offices is often part of a larger change towards more flexible and multi-locational working (Blok et al., 2012; van der Voordt, 2004). The increased flexibility and freedom may explain some of the benefits that are observed in non-territorial offices in comparison to open-plan offices with assigned workstations (Bodin Danielsson & Bodin, 2008; Kim et al., 2016), making it difficult to distinguish the effects of the physical office design from other variables. Furthermore, the benefits of workspace variety and flexible working are probably partly intertwined because the adoption of a more mobile and paperless working style will also help the worker to use different workspaces in the intended way. Although there was limited empirical data to evaluate the role of these factors, it seems that the development of work also contributed to the positive results in Organization A (Study V). Thus, advances in the way of working, including the organization and management of work as well as the technical solutions, also have a role in developing workplaces towards more comfortable environments that facilitate the performance of office workers.

5.3 Strengths of the studies

This thesis has provided novel information on a range of previously little-investigated topics both in the area of experimental laboratory research and field studies. The experimental studies were among the first to explore the relation between the *STI*, cognitive performance and subjective disturbance. The realistic building of experimental conditions to test the effects of the *STI* (Study III), the investigation of a general relation between r_D and perceived noise in open-plan offices (Study IV) and the detailed analysis of two office relocations and the mediating mechanisms (Study V) are, to date, unique in their approach and methodology. This thesis provides important information for evaluating acoustic problems but also addresses some solutions for improving the acoustic conditions.

The main strengths of this study are related to its practically oriented interdisciplinary approach. Ecological validity was the main priority in designing the studies because it is a prerequisite for any successful practical application. Determining speech intelligibility by the *STI* greatly increases the applicability of the results compared with studies that only characterise speech intelligibility in qualitative terms (e.g., low versus high). Throughout the years, the research questions have been influenced by continuous contact with and feedback from real workplaces and different professionals working with open-plan offices. The findings are relevant to a wide audience involved in the design, development and evaluation of open-plan offices, including facility owners and managers, workplace managers, interior designers, architects, acoustic consultants, developers and manufacturers of acoustic products, HR representatives, occupational health care, occupational safety personnel, and individual workers interested in these issues. The results can also be applied in the development of room acoustic target values and national building codes.

The interdisciplinary approach adopted in this thesis is relatively rare, particularly as it includes both laboratory and field studies. Especially the field studies of open-plan offices tend to lack relevant physical measurements or even a sufficient description of the investigated workspaces (for exceptions, see Bodin Danielsson & Bodin, 2008; Veitch et al., 2007). This greatly weakens the generalisability of the findings and may lead to the misinterpretation of the results by other researchers. In this thesis, the physical conditions were quantified with rigorous and relevant room acoustic measures in Studies I to IV, and the offices of Study V were described in detail.

There were several benefits in combining different types of measures (cognitive, subjective, room acoustic) as well as different study types (laboratory experiments, field studies). The effects of office noise were approached from several points of view leading to versatile evidence of the phenomena. As all research methods inevitably include some weaknesses, this approach provides a more balanced and reliable view because complimentary information is available for evaluating single findings. This strengthens the conclusions that can be drawn from this thesis. Of equal importance, the research methods revealed some important limitations of the examined issues. The use of different tasks, instead of relying on the serial recall task only, showed that the model of Hongisto (2005) may be restricted to short-term memory and working memory tasks. The observation that the *STI* cannot be decreased efficiently between neighbouring workstations has important implications for room acoustic and office design, particularly if the critical *STI* is lower than 0.50 in some tasks. The results of Study V demonstrate the limited role of room acoustic design by showing that two offices with similar room acoustic conditions may differ greatly, and that complementary ways are needed to improve satisfaction with the work environment.

The theoretical contributions of this work concern particularly Hongisto's (2005) model but also the role of office distractions and impaired collaboration as possible mediators of other negative outcomes reported in the literature. The results of this thesis support the *STI*-performance model but suggest that it may be restricted to short-term memory and working memory tasks and to constant masking sounds.

5.4 Limitations and suggestions for future research

Each of the studies has specific methodological limitations that are discussed in the original publications. In the following, I will focus on general issues that are relevant to the conclusions of this thesis as a whole.

The key question in laboratory experiments is the generalisability of results to real-life settings. Even though practical relevance was emphasised throughout the design of the experiments, it needs to be evaluated critically. First, the validity of the experimental tasks is an important issue. In the choice of tasks, one has to balance between well-established cognitive tests that do not closely resemble office work (e.g., serial recall) and more office-like complex tasks which are less researched and likely have weaker psychometric properties. The present studies included both types of measures but effects were only observed in the short-term memory and working memory tasks. Along with other researchers (Liebl et al., 2012; Schlittmeier & Hellbrück, 2009), it was suggested that results from these tasks might predict performance in office work because more complex tasks rely on such basic processes. However, Sörqvist (2015) discusses several arguments against such 'sub-component view' of noise effects, concluding that researchers aiming to understand complex performance in applied settings should employ tests that mimic those tasks. In the present studies, the generalisation of results from short-term memory and working memory tasks to more complex performance is contradicted by the observation that none of the complex tasks were objectively affected. However, this might also be explained by any differences in reliability between tasks.

Realistic office tasks are difficult to develop, particularly for repeated-measures designs where several task versions with identical properties are needed. In addition, the quantitative measures used in such tasks may not capture the essential processes involved. For example, some researchers have observed effects of speech intelligibility in a story-writing task (Keus van de Poll et al., 2014, 2015) which seems relevant to applied settings. However, these results are only based on a quantitative analysis of performance (e.g., number of characters in the text) instead of the quality of text which might be more important in practice. In future studies, eye-fixation monitoring could be one way of gaining more information on the disruption of cognitive processing, instead of only the end result, in more complex tasks, such as reading or writing. Hyönä and Ekholm (2016) offer an example of a study in which eye-movement tracking, but not a comprehension test done at the end, revealed a disruptive effect of background speech on reading.

Another area of generalisability concerns the groups and settings into which the results can be applied. The participants of the laboratory experiments were students, not office workers. Due to their age and some health-related criteria, they were presumably healthier than the working population in general. This is a common limitation in experimental psychology. However, the misrepresentation of the working population would pose a bigger problem if the use of students overestimated the effects of noise. It is more likely the opposite.

Some of these limitations could be overcome by measuring cognitive performance of office employees at their own offices. Such study has been conducted by Seddigh, Stenfors et al. (2015). In their study, over 500 office workers performed a memory test at their own workstation following a link sent by e-mail, first in quiet and later in normal working conditions. Although this is a very interesting study, the methodological weaknesses of such a design are obvious as the researcher loses control over the experimental conditions and the participants become aware of the research question which may bias their behaviour. Nevertheless, the development of methods that would enable the investigation of performance effects in real office environments, preferably performing authentic work tasks, is an import avenue of future research.

This thesis focused on investigating the effects of noise in a way that could be applied in acoustic and office design on a general level. This meant that the role of individual differences was mostly excluded from the scope of this research even though these differences also have practical implications. For example, hearing impaired and noise sensitive individuals might require different or additional noise abatement measures. Information about the effects of office noise among these groups would be important for workplace managers and designers as well as professionals in HR and occupational health care.

In Studies I, II and III, it was suggested that some of the tasks were not affected because of compensatory efforts, referred to as latent performance decrements by Hockey (1997). This argument is problematic in terms of falsifiability: it can be used to support the hypothesis of the effects of noise on performance in the absence of any objective evidence as long as some subjective effects are observed in the same conditions. Subjective disturbance and increased workload were assessed in this thesis but they can only be considered as indirect indicators of compensatory effort. The latent decrements of performance could be examined more directly, for example, by assessing subsidiary task failures, shifts to simpler strategies and fatigue after-effects of noise (Hockey, 1997). The investigation of compensatory efforts might also shed more light on the mechanisms through which office distractions are associated with stress symptoms in open-plan offices (Study V).

The room acoustic methods also involve some limitations. As has already been noted (Section 5.1.1), the method of calculating the *STI* is most appropriate for constant masking sounds. In the future, more emphasis should be placed on the analysis of the temporal characteristics of masking sounds as well as on adaptive masking solutions. In addition, the r_D may have overestimated speech intelligibility in the observed office conditions (Studies IV and V) because its calculation assumes normal voice effort. According to the measurements of Warnock & Chu (2002), workers tend to lower their voices in open-plan offices which has a direct impact on the *STI* of speech. Other simultaneous speakers also create some masking effect and decrease the intelligibility of single voices (e.g., Keus van de Poll et al., 2015). Taking into account the human activity noise results in lower *STI* than measurements based on the ISO 3382-3 standard (Dehlbæk, Jeong, Brunskog, Petersen, & Marie, 2016). Due to this, the results cannot be directly generalised to call-centres or similar workplaces with constant babble.

The strong practical emphasis also included some drawbacks. The quality of the experiments would have benefited from more pretesting and development of the questionnaires and tasks before the actual experiments, particularly as there was little previous research to rely on. The aims of individual experiments were ambitious which resulted in complex designs in Studies II and III. However, these decisions were affected by the resources that were available at the time. Both field studies were retrospectively designed because the research questions could not be anticipated when the data were originally gathered. Studies similar to IV and V should be conducted with a uniform design and research methods.

Future studies should continue to investigate the mechanisms linking office noise to other problems observed in open-plan offices, such as employee well-being. The potential of room acoustic design in decreasing these problems should also be explored. Researchers should focus more on examining the role of specific factors related to the design and use of office spaces. Such information would complement studies comparing general office categories. The relation between modern office designs, perceived acoustic environment and employee well-being remains a relatively little-researched topic, particularly as it involves a complex interplay between elements related to the changing nature of work and organizations.

5.5 Conclusions and practical implications

This thesis has shown that office noise, particularly background speech, causes subjective disturbance and impairs performance, at least in verbal short-term memory and working memory tasks. Office distractions are not only a risk for environmental dissatisfaction but are associated with impaired collaboration and increased stress symptoms.

Taken together, employee needs for concentration and privacy should have more priority in the design of modern offices where open workspaces are used. The acoustic conditions of open-plan offices can be improved by room acoustic design that includes the use of absorption materials, screens, and masking sound. Constant and neutral masking sounds do not increase noise complaints but are associated with improved acoustic satisfaction because a higher background sound level decreases the intelligibility of background speech.

Satisfaction with work environment and acoustic conditions can also be improved by providing additional quiet workspaces at open-plan offices. Attention should be paid to the number of quiet workstations and the ease of workspace switching which requires proximity to such spaces. If workers retain assigned workstations, some compromises may have to be made in space-efficiency to support employee satisfaction, as a considerable amount of space is needed for alternative quiet workspaces. The provision of additional workspaces and room acoustic design should not be viewed as alternatives but used in combination to improve possibilities for concentration and speech privacy.

However, the best conditions for concentration are achieved when background speech is completely absent. The possibility of using alternative quiet workspaces may not be sufficient for all employees. Private rooms may still be the optimal workspace for individuals whose work encompasses mainly individual tasks with high concentration demands or individuals who are particularly sensitive to noise and other distractions.

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